Response to RC1

Soil slope monitoring with Distributed Acoustic Sensing under wetting and drying cycles

Discussion: https://doi.org/10.5194/egusphere-2025-1725

Comments from the reviewers are given in black.

Our responses are given in blue. *The revisions to be made in the manuscript are given in italic style.*

General Comments:

The manuscript presents a multi-month DAS deployment on a grass-covered slope in central Switzerland. By pairing high-frequency (>1 Hz) ambient noise interferometry with low-frequency (<1 Hz) quasi-static strain measurements, they aim to demonstrate that DAS can be used to "track real-time volumetric changes in response to both long-term and daily cyclic moisture variations". The topic is very timely and relevant to both the DAS and geohazard communities. The integration of surface wave inversion, dv/v monitoring, and low-frequency strain analysis are technically sound. The dataset is extensive and novel, considering the longer-term duration of the low-frequency DAS measurements combined with near-surface moisture sensors. This work is an important contribution and represents a comprehensive overview of the complementary techniques that can be implemented using DAS to inform slope stability monitoring.

However, there are some critical issues that need to be addressed, relating to the author's interpretation of (1) progressive soil consolidation during drying periods, and (2) daily cyclic deformation patterns driven by moisture fluctuations, as follows:

Thank you so much for your constructive comments. Your review has been instrumental in helping us deepen our analysis of the DAS measurements and address important aspects we had previously overlooked. We believe that your suggestions have significantly improved the clarity, completeness, and overall quality of the manuscript.

Temperature effects: The authors indicate that the cyclical deformation patterns observed in the low-frequency DAS strain are driven by moisture fluctuations between daytime drying and nighttime moisture recovery, not by temperature variations. The effect of temperature variations are neglected after estimating that the daily temperature variations (within 1°C) would induce a strain change of about 1.1 x 10^{-2} millistrain which is more than two orders of magnitude smaller than the daily strain variations measured by the DAS system. However, this represents an approximation based on the properties of silica-based fiber, and does not account for the response of the DAS interrogator and fibre optic cable (see next point). Further to the above, the cyclical pattern of the low-frequency strain observations occurring across all channels (Figures 3, C1 and C2) as well as the known sensitivity of low-frequency DAS to temperature, suggest that temperature is a likely dominant contributor.

Thank you for raising this important question regarding temperature effects. Our initial temperature correction was applied only to account for the equivalent strain induced in the cable itself. We also found an error in estimating the relative contribution of temperature to cable strain. The 1.1 x 10^{-2} millistain ended up only one order of magnitude lower than the daily variation of strain which is around 0.1 millistain. We revised this section accordingly and applied the thermal correction to the average strain signal. Please see Fig. 8 referenced in the response to the next comment.

Regarding the cyclical pattern observed in the low-frequency strain data, we address this in detail in our response to the following comment.

Interrogator Instrument Response: The application of low-frequency DAS for monitoring soil slope processes is still emerging. Here, the authors rely on a two-month period of continuous data acquisition using a Silixa iDAS for the measurements, which provides a measurement of strain-rate. However, the reliability and performance of DAS to measure strain and strain-rate over longer periods is still poorly understood. Ouellet et al. (2024) inferred relative displacements from the LF-DAS using another type of DAS interrogator and were able to obtain reasonable comparison with insitu displacement sensors (ShapeArrays) over a ~three-day period. In this study, there are no collocated sensors that support calibration or confirmation of the strain measurements (e.g., strain gauges, inclinometers, survey prisms), which would be important both for the interpretation and justification for the neglect of temperature. The native strain-rate measurements are integrated to derive strain over the duration of the acquisition. However, this also enables the accumulation of potential noise in the strain-rate data to accumulate over time and appear as drift. The monotonic decrease that is observed in the strain data may be a result of instrument drift, and not representative of true strain. At a minimum, the authors should address this point by including a discussion of the potential of instrument drift or consider relying on the native strain-rate measurements for their analysis and interpretation. It may also be worthwhile to compare the strain-rate measurements with the gradient of the temperature (temporal derivative) over a shorter time interval, for a more careful assessment of the relationship between the two measurements. The monotonic decrease of strain across all channels over the two-month period does not seem credible, considering both the spatial variability of the cable over the slope as well as the temporal variability considering the numerous rainfall events occurring over the period. For example, considering the nanostrain-rate sensitivity of the DAS measurements, gravity-driven processes of the slope over the two-month period with a shallowly buried cable should incur some observations of visible tension and compression in the strain data, aligning with the topographic profile along the length of the cable over the two-month period.

Response to Comment on Interrogator Instrument Response:
Thank you so much for pointing this out! We really appreciate the opportunity to improve our manuscript further with instrument response correction. We have revised **Section 6.1** accordingly to address these concerns and added Fig. 8 to support this discussion. Furthermore, we replaced all the figures afterwards with instrumental drift correction. The change in trend remains clearly visible, which strengthens our analysis of the long-term trend.

“”””

6.1.1 Instrumental drift quantification
The analysis of long-term accumulated strain requires careful consideration of potential instrumental drift. To quantify this, we used the cable section that remained isolated from ground deformation, looped, and hung on a pin within the garage hosting our interrogator. This section serves as a reference to isolate instrument-related effects from ground strain. Figure 8a shows the accumulated strain change for both the buried sections (A, B, and C) and the garage section. A consistent monotonic decrease in strain, superimposed with intraday cyclic variations, is evident across all channels. The strain variations among the 80 channels within the garage (Fig. 8a, green lines) are highly coherent with minimal time shifts.

To isolate long-term strain change from diurnal fluctuations, we applied Seasonal-Trend decomposition via LOESS (STL) (Cleveland et al., 1990) to the averaged strain from both the buried and garage sections. This method separates the time series into trend, daily periodic, and residual components. The resulting long-term trend of the garage section exhibits a linear decrease (Fig. 8b). A linear fit to this trend reveals a constant instrumental drift rate of -7532 nanostrain/day.

The long-term trend of the buried cable section deviates from this linear pattern, suggesting that it records both the instrumental drift and non-linear ground deformation. The subsequent analysis of the buried cable data will be presented after correcting for instrumental drift.

6.1.2 Temperature effects on the fiber-optic cable

DAS signals below 1 Hz are influenced by both strain changes along the cable and temperature effects (Bakku, 2015; Gao et al., 2018; Leggett et al., 2022; Sidenko et al., 2022). Temperature effects can introduce bias into strain measurements if not accounted for. As such, analyzing and correcting for thermal effects is critical for reliable interpretations of strain variations. We first assessed this empirically by comparing the daily residual strain of the garage section with direct air temperature measurements (Fig. 8c showing the period between August 12 and 19, 2023). This comparison shows a high correlation. We calculated the ratio of the daily strain change to the daily temperature change. This yielded an observed apparent temperature sensitivity of within $\pm 1 \times 10^{-2}$ *millistrain/°C. However, as the garage's thermal environment is different from the open air, this section cannot serve as a source for direct quantitative correction of the buried cable.*

To quantify the theoretical impact of temperature on the buried cable, we follow the approach of Leggett et al. (2022). Adopting the parameter settings of Carr et al. (1990), we calculated the equivalent strain variation induced by temperature fluctuations using the relation

.... (equations for thermal correction)

In this study, ground temperature measurements were taken every 10 mins at EMM_2 at 0.15 m depth. Daily temperature variations were within 1 °C, inducing a strain change of about 1.1×10^{-2} *millistrain. This value is similar to the sensitivity observed in the garage section and is approximately one order of magnitude smaller than the primary daily strain variations measured in the soil.*

We applied a thermal correction to the buried cable data by subtracting the calculated temperature-induced strain. The result is shown in Fig. 8d, which compares the final, temperature-corrected daily residual strain with the uncorrected *strain. The two curves are nearly identical, confirming that the influence of direct temperature changes on the fiber is minimal.*

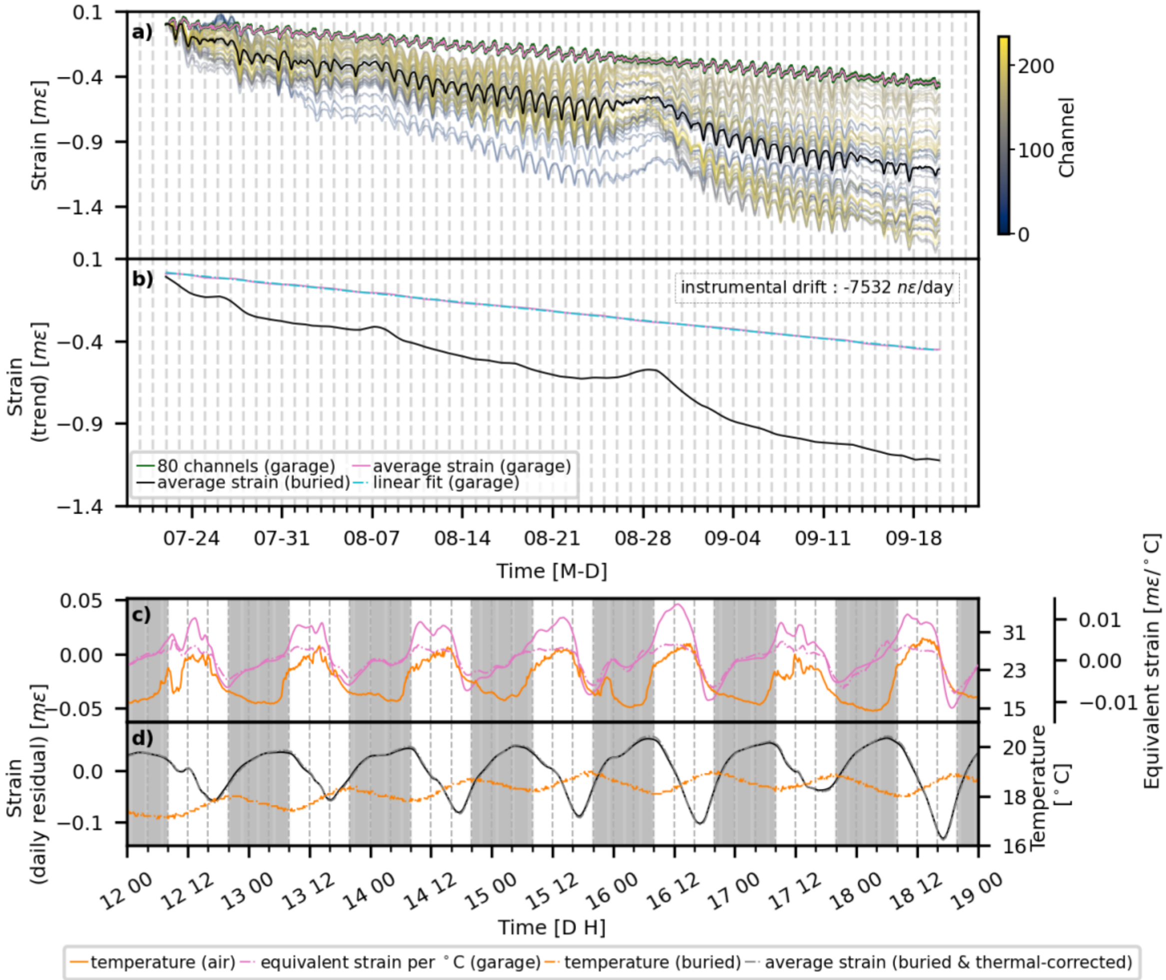

Figure 8. Relative strain variations. (a) displays the relative strain across DAS channels. The colored lines (blue-to-yellow gradient) represent the 10-channel averaged strain for the buried section. The dark green lines show the strain of the 80 channels of the garage section, with their average plotted in pink. The variation among the channels is so minimal that the individual green lines are nearly indistinguishable and overlap. (b) shows the long-term relative strain trends for both cable parts. The dashed cyan line is a linear fit to the average strain of the garage section, with the daily change indicated in the top right. (c) provides a zoomed-in view of the daily variations (August 12-19, 2023) for the garage section. The plot compares the daily residual strain (pink line) with the air temperature (orange line). The right axis quantifies the cable's thermal sensitivity in terms of equivalent strain every 1°C, indicated with pink dashed line. (d) shows daily variations for the buried section over the same period. The plot compares the daily residual strain (black line) with the ground temperature measured at 0.15 m depth (orange line). The thermal-corrected

strain is shown in a dashed gray line. For (c) and (d), shaded regions indicate nighttime (18:00-08:00 UTC).

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Response on the Monotonic Strain Trend

We acknowledge that gravity-driven processes would typically produce spatially variable tension and compression. However, the monotonic strain decrease is observed not only on sloped sections (A and C) but also on the flat section B, where the strain change is not aligned with the direction of gravity. We therefore attribute this monotonic strain variation to volumetric deformation of the soil.

Response on the cyclical pattern related to temperature change

We agree that thermal-induced stress from the surrounding soil is an important mechanism to consider. However, if soil expansion and contraction were the dominant factor, strain would be expected to correlate positively with temperature as shown in Fig.8c. Our data reveal the opposite (Fig. 8d) and this indicates that thermal-induced soil stress is not the primary driver of these observed variations.

Cable Instrument Response: Please include the specifications of the fiber optic cable used in this study. Particularly at low frequencies, the type of cable also plays an important role in the instrument response (e.g. tight-buffered versus loose-tube, see Ouellet et al. 2024). The impact of the cable type on the response should be included in the discussion.

The cable used is gel-filled non-metallic loose tube cable. We have added the discussion of the cable impact at ~L360 as follows:

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Although the absolute strain magnitudes are underestimated due to the low strain transfer efficiency of the loose-tube cable (Forbriger et al., 2025), this underestimation acts as a consistent scaling factor and does not affect the interpretation of relative patterns.

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Gauge length effects: A channel spacing of 1 m and gauge length of 10 m is used in this study. Why were these data acquisition settings used? A gauge length of 10 m could mask any localized changes in moisture. The author's conclusions (L405) that "This enables direct field-scale observations of soil mechanical response at sub-meter resolution" are technically incorrect, considering the settings (1-m channel spacing, 10-m gauge length) used in this study. The impact of the 10-m gauge length on the results should be included in the discussion, notably in comparing or integrating these measurements with point-based sensors, as for the effective stress-strain response.

The gauge length of iDAS interrogator we used is a fixed parameter. We have changed the phrasing (L405) to "meter resolution" and added this part in the second paragraph of the conclusions:

""""

The 10 m gauge length, a fixed parameter of the iDAS interrogator, functions as a spatial moving average over a 10 m segment of soil. It filters out localized, small-scale heterogeneities and improves the signal quality for observing the bulk soil response but inherently limits the spatial resolution of the strain measurement. This averaging effect is a crucial factor when integrating DAS with traditional point-based instruments. Future near-surface studies targeting more localized phenomena would benefit from deployments using interrogators with a configurable and shorter gauge length.

""""

Coda wave interferometry: The dv/v estimates are computed with daily cross-correlation waveforms. As such, they cannot resolve sub-diurnal moisture cycles and therefore the claim that the author's key observations of "daily cyclic deformation patterns driven by moisture fluctuations" is supported by the dv/v analysis, appears invalid. Further to this, the dv/v are computed in the 8 to 16 Hz frequency range. The fundamental mode sensitivity kernel (Figure A2b.) appears to indicate varying dv/v sensitivity from 0 to 12 m, extending well below the partially saturated zone in the upper metres. The insitu sensors providing moisture measurements only extend up to ~1 m. The rock physics-based model of dv/v relies on a two-layer soil profile extending to a depth of only 1.38 m. Considering the known sensitivity of dv/v to greater depths (from the sensitivity kernel) it seems important to address this discrepancy more thoroughly in a discussion, or improve the model by extending to a similar depth as the dv/v.

Thank you for these insightful comments. We agree that our daily-stacked CWI dv/v analysis cannot resolve the sub-diurnal cycles and revised L396 accordingly: *"The long-term soil consolidation is further supported ... "*

The two-layer soil profile corresponds to the inverted soil depth along the slope. It would require rock moisture variations to extend the RPM model deeper into the weathered rock layer. However, we do not have the necessary data from large enough depths to force such a model during the monitoring period. We believe this discrepancy is critical to explain why the CWI-derived dv/v changes are smaller than the RPM-derived dv/v. We have added the following discussion L325 to clarify this important point.

""""

The difference in response times and magnitudes between the two models is primarily due to their different depth sensitivities. As shown by the sensitivity kernel (Fig. A2) the CWI-derived dv/v in the 8-16 Hz frequency band is influenced by velocity changes throughout the upper 12 m, including both the soil layer and the underlying molasse conglomerate. The RPM is limited to a simplified two-layer soil model extending to 1.53 m where the moisture changes are expected more significant compared to the 12 m depth. This explains why the RPM predicts larger dv/v fluctuations than CWI. While a more complex, deeper model would be ideal, we do not have the necessary data from large enough depths during the monitoring period.
""""

Specific Comments:

Topographic Profile: It would be helpful to include a topographic profile or elevation cross-section along the cable route. This would improve interpretation of both seismic and low-frequency strain data, particularly in understanding how slope angle and local relief may influence stress distribution, hydrological changes, and strain patterns.

The topographic profile is given in Fig. 2c. We also provide a figure with spatiotemporal plot of strain-rate together with the topographic file in the next response.

Spatiotemporal Strain-Rate Images: To support interpretation of the low-frequency DAS data, it would be helpful to include a spatiotemporal plot of strain-rate over the entire acquisition period. This would help readers visually assess both temporal variability and any spatially coherent patterns.

Thank you for this suggestion. We have prepared the spatiotemporal plot of the strain rate for your review. The plot shows that the dominant temporal variations are coherent across most channels. This supports our argument that the observed changes are driven by a dominant hydromechanical response rather than localized, topography-driven mass movements. The spatial uniformity of the temporal signal is demonstrated in Fig. 8. To maintain the manuscript's focus, we believe that this new figure does not bring added value and prefer to leave it out.

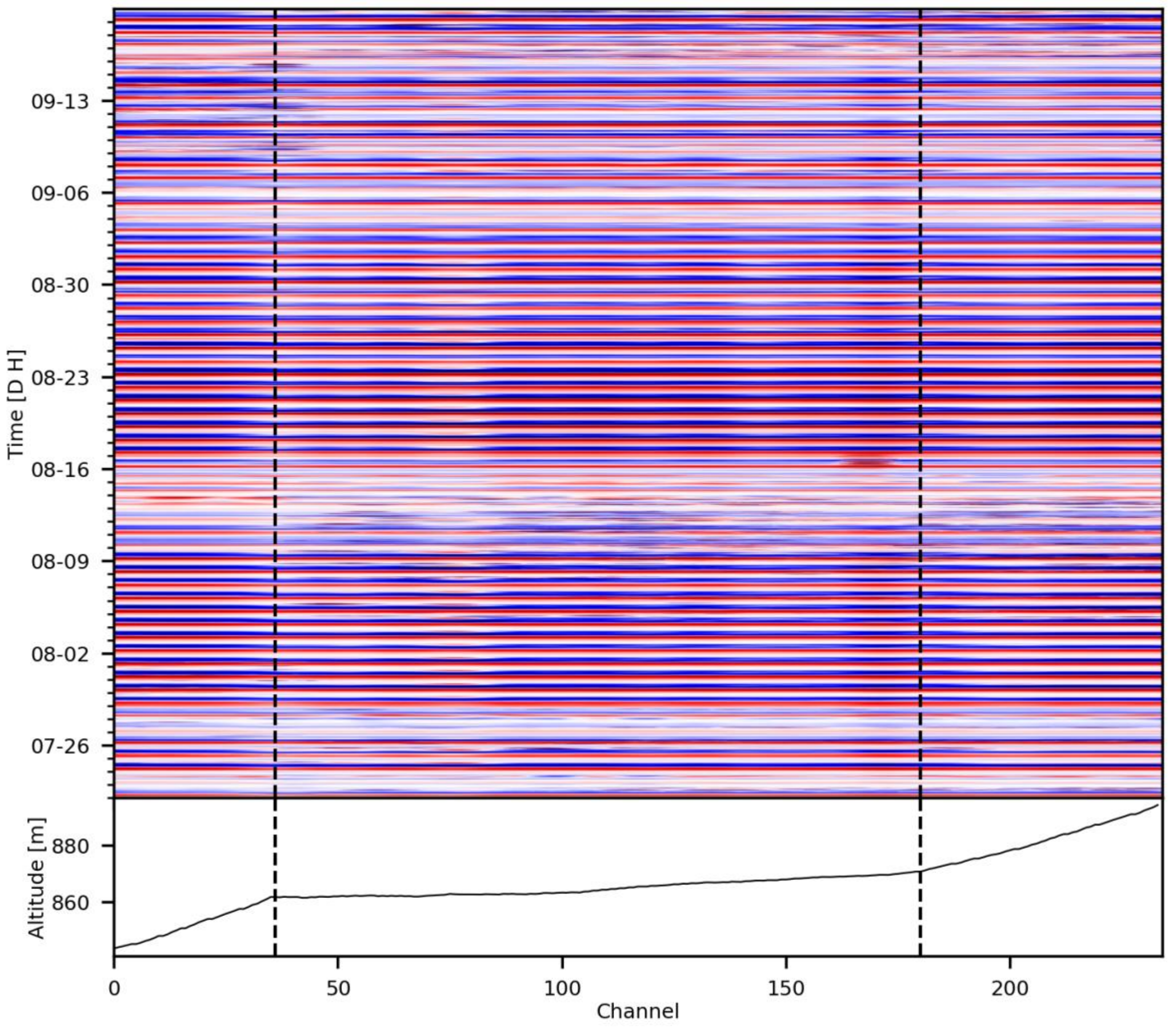

Figure 3c: In addition to the cyclic signals (occurring over all channels), rain-induced high amplitude signals (associated with rainfall events) and

quasi-static cow signals, there appears to be a fourth type of signal (positive strain-rate signals occurring at multiple channels over short time periods that are not associated with rainfall events). Please comment on these signals and whether they are attributed to moisture changes or other processes.

We have marked the fourth type of signal on the figure. Those short-period positive strains correspond to small perturbations in SWP measurements and thus also result from moisture change. We added the description around L165 as follows:

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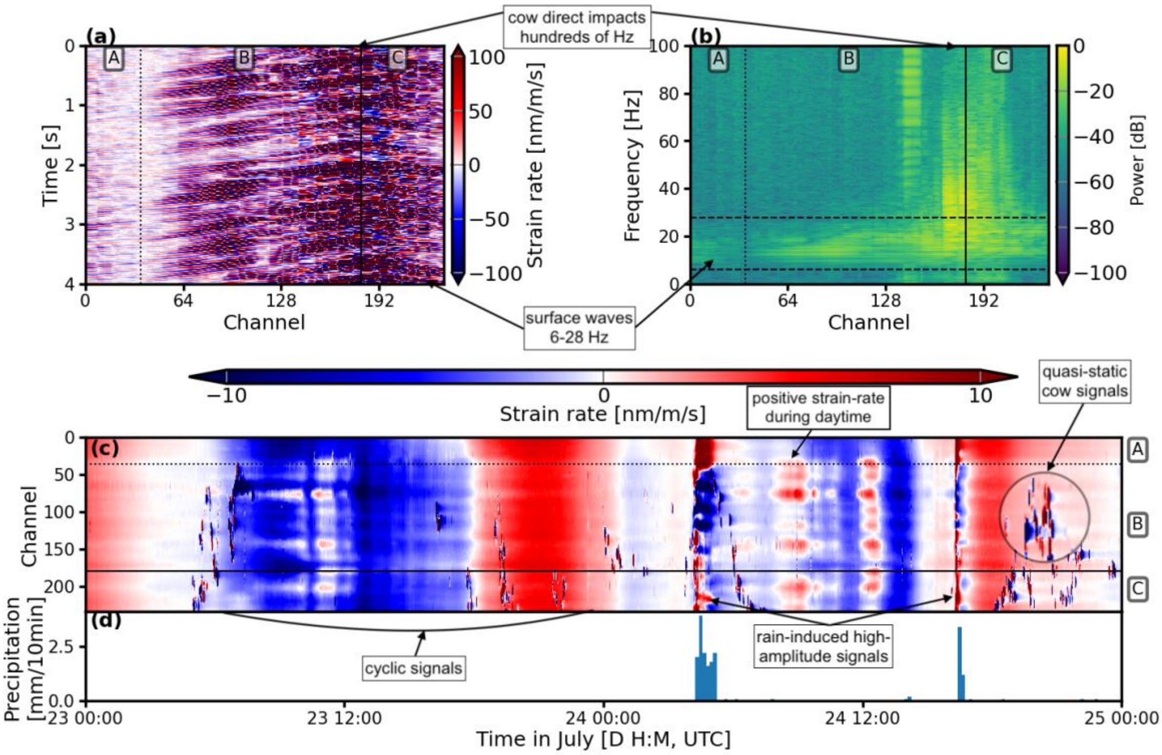
Additionally, there are short-duration positive strain rate values during the daytime. These short-duration signals are most prominent during daytime hours, where they are superimposed on the broader negative strain-rate background.



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We also added the interpretation of those signals after L315:

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Returning to the signal types identified in Fig. 3c, we can now attribute them to hydro-mechanical processes driven by soil moisture changes at different timescales. The slow, diurnal strain cycles are consistent with effective stress variations due to day and night moisture change, while the abrupt, high-amplitude signals are direct responses of pore water pressure to infiltration from rainfall. The short-period positive strain-rate values correspond to small, rapid daytime perturbations observed in the SWP data.
""

Section 2.1.1, Line 106 – Spatial Heterogeneity: The authors state that "spatial heterogeneity on the slope further complicates effective stress distributions." However, the key observations of cyclical strain observations appear generally spatially homogenous across channels. Given DAS's advantage in spatial resolution, it would strengthen the paper to highlight any observed heterogeneity in strain or inferred stress response. Do spatial variations in the LF-DAS signal align with known heterogeneity in vegetation, soil type, or moisture content?

Our discussion of heterogeneity focuses on the comparison across two dry periods at around L380 with Fig. 9f. We observe consistent time shifts of intraday strain variations between the two drying periods across multiple channels. This suggests spatial variability which would be valuable to compare with detailed spatial maps of soil type or moisture content. Such maps, however, were not available.

Section 7.2. Effective stress-strain response. This section would benefit from greater clarity on the input data and analytical steps. Is the effective stress calculated using Equation (1) based on measured VWC and SWP? Is the associated strain derived from the LF-DAS data, and if so, is this averaged over the full array or selected channel segments? Explicitly stating this would help improve the clarity of this section.

We have modified L352 to improve clarity with:
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We used the effective stress calculated at 0.15 m and the average strain over all DAS channels for comparison (Fig. 8d-e).
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To clarify our final calculation on effective stress, we have also added the adapted equations for effective stress after L295:

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We adapted it using VWC and SWP values to calculate each term as follows (neglecting air pressure):

$$P_e = \rho_e g h - \frac{VWC - \theta_r}{\theta_s - \theta_r} SWP$$

where h=0.15 m is the measurement depth, ρ_e is the effective density of the soil, calculated as $\rho_e = (1-\phi)\rho_a + \phi(\frac{VWC-\theta_r}{\theta_s-\theta_r}\rho_w + (1-\frac{VWC-\theta_r}{\theta_s-\theta_r})\rho_a)$ (Eq. 4). Here, the densities (ρ_s, ρ_w, ρ_a) and porosity (ϕ) are given in Table B1 and B2. $\theta_r = 0.559$ is the residual water content from field measurements (Wicki et al., 2023). The saturated water content θ_s is taken as the average of max(VWC) and ϕ.

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Depth sensitivity of dv/v: Since the dv/v analysis is performed in the 8–14 Hz frequency band, it would be useful to include an estimation of the corresponding sensitivity depth range. This would support statements such as that on Line ~325: "This suggests that seismic waves integrate the water infiltration process throughout the soil profile rather than merely reflecting near-surface saturation." This could be completed by referring to the fundamental mode sensitivity kernel shown in Figure A2. b).

We have changed this part of discussion as mentioned above at L325.

Groundwater Level Information: Is there any information available on groundwater levels at the site? Even approximate values or nearby hydrological data would help constrain interpretations of the dv/v changes and assess whether infiltration events reach the saturated zone.

Thank you for your suggestion. A groundwater penetration test was carried out at site EMM_1 several years ago, but the water table exceeded the instrument's measurement limit of approximately 5 meters. To our knowledge, the nearest available piezometer data, from Hasle-Schächli located 12.8 km away, indicate a groundwater level of around 562 m a.s.l.—more than 200 meters below our study site. Based on this information, groundwater influence was not included in the present analysis.

L270: Ouellet et al. (2024) follow the approach described by Leggett et al. (2022) in their study. It may be more appropriate to cite the original reference of Leggett et al. (2022) here.

Thanks, we have modified this.

Section 6.2, L285: "The intraday strain variations (Fig. 8f) contrast with previous findings ..." Figure 8f is difficult to see within the overall figure. Consider making this into a larger figure, complete with axis labels and values for clarity.

We have removed Fig. 8f and added a new figure (Fig. 8d) above.

L405: The statement, "In conclusion, DAS integrates traditional seismic wave analysis with continuous monitoring of quasi-static deformation" should be revised to, "In conclusion, we integrate traditional seismic wave analysis with continuous. monitoring of quasi-static deformation using DAS".

We have made this change to L405.

Technical Corrections:

Section 5.2, Line ~225: "We focused on ch80 for each day because of its clear separation between direct arrivals and coda waves (Fig. 6a)." Which channel(s) was cross-correlated with ch80 to obtain the cross-correlations? It does not appear to be specified in the text.

Ch165 was used as the virtual shot. We have changed L227 to:

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We focused on ch80 for each day with ch165 as the virtual source ...
""""

Appendix C, Table C1. Index of fraction - should be Index of refraction

Thank you. We have changed it to index of refraction.

As an additional consideration for the authors', it may help to improve the clarity and impact of the manuscript by separating the seismic (>1 Hz) and low-frequency (<1 Hz) analysis into two separate studies. For instance, the extending the dv/v model over a greater depth and focusing on both the near-surface (0 to 2 m) and deeper (2 to 12 m) sensitivity of the dv/v to changes in effective stress represents an important contribution to the field of environmental seismology. Similarly, improving the analysis and interpretation of the low-frequency DAS observations, with a more rigorous evaluation of the temperature effects, alongside the cable and instrument response, represents a novel study. Separating the two analyses could help improve the clarity and impact of the overall findings.

We appreciate this thoughtful suggestion regarding the manuscript's structure. In this study, we chose to present the seismic and low-frequency analysis together because they offer complementary insights. The dv/v analysis provides depth-integrated sensitivity to subsurface velocity changes, while the low-frequency DAS data offer more localized, directionally sensitive strain-rate observations. Together, they enable a more holistic interpretation of moisture-driven processes. Given the current scope and available data, we do not believe the two analyses are substantial enough for separate studies, but we appreciate the reviewer’s perspective and will consider this direction for future, more targeted studies.

Additional References:

Thomas Forbriger, Nasim Karamzadeh, Jérôme Azzola, Emmanuel Gaucher, Rudolf Widmer-Schnidrig, Andreas Rietbrock; Calibration of the Strain Amplitude Recorded with DAS Using a Strainmeter Array. Seismological Research Letters 2025; 96 (4): 2356–2367. doi: https://doi.org/10.1785/0220240308