Response to RC2

**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:**

This manuscript presents results from a two-month field deployment using Distributed Acoustic Sensing (DAS) to monitor a soil slope under natural wetting and drying cycles. The study captures both long-term and daily hydromechanical deformation, combining surface wave inversion, coda wave interferometry, and effective stress modeling. Integration with in-situ moisture data reveals soil "breathing" and progressive stiffening during drying. The paper is well written, the methods are clearly described, and the results are well illustrated. The findings are relevant for understanding moisture-driven soil behavior and slope stability. I only have a few concerns regarding the depth sensitivity of the data and the application of the rock physics model to interpret dv/v changes, which I believe should be addressed more clearly before drawing detailed interpretations.

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.

**Specific comments:**

- **Depth sensitivity of surface wave inversion and soil moisture sensor:**

Please provide more detail about the soil moisture sensors used in the study—specifically, the measurement depths, the type of sensors, the quantities they measure directly, and whether any scaling or calibration is needed to derive VWC. Since the sensors are not co-located with the fiber-optic cable and are installed in different slope settings, what is the justification for focusing on the 0.15 m depth in the comparison? Line 170 states that 0.15 m depth is chosen because of the cable installation depth, but given that DAS measures strain from propagating waves (which integrate energy over depth and wavelength), how is the physical cable depth directly related to the depth sensitivity of the seismic measurements?

Thank you. We have updated the paragraph beginning at L146 as follows. The soil moisture measurement at 0.15 m depth was selected for calculating effective stress for coupled analysis with low-frequency DAS data. This choice is based on the burial depth of the fiber-optic cable (0.1-0.2 m). The low-frequency DAS signals analyzed here are induced by quasi-static soil deformation in response to environmental loading (e.g., moisture changes) rather than seismic waves.

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*Since April 2019, point-measurements of soil moisture have been conducted at a 10 min interval near the top of the slope, close to the malfunctioning cable section (EMM_1), and in a flat area adjacent to the loafing shed at the slope toe (EMM_2) (Fig. 2b) (Wicki et al., 2024). VWC was derived from dielectric permittivity measurements following Topp et al. (1980), using capacitance-based sensors (ECH2O 5TE, METER Group). SWP was recorded with tensiometers (T8 Tensiometer, METER Group), which measure pressure differences in the soil with a piezoelectric sensor embedded in a water-filled porous ceramic cup. At EMM_1, two sensors of each type (2 × VWC and 2 × SWP) were installed at depths of 0.15 m, 0.30 m, 0.50 m, and 1.00 m. At EMM_2, two sensors of each type were installed at 0.15 m, 0.50 m, and 1.00 m, with an additional sensor pair (1 × VWC and 1 × SWP) installed at 0.20 m and 0.70 m. No site-specific calibration of the sensors was conducted, as the original study by Wicki et al., (2024) focused primarily on relative changes in VWC. While this study used absolute values to estimate effective stress, only relative changes in effective stress were analyzed for comparison with the strain rates derived from the DAS measurements.*
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In Figure 5d, the surface wave inversion results appear to have limited resolution in the upper ~2 meters, yet dv/v is compared to moisture changes at 0.15 m depth. Can you clarify this mismatch in depth sensitivity? Also, please provide an estimate of the seismic wavelength of the surface waves used for dv/v analysis. For instance, if the dominant frequency is ~10 Hz and shear wave velocity is ~200 m/s, the wavelength would be ~20 m—much deeper than 0.15 m. Do you have sensor data at greater depths to better match the depth sensitivity of the seismic measurements?

In Figure 5d, the inversion results show that the soil layer depth is approximately 1.53 m. Based on that, the CWI-derived dv/v is compared to a two-layer soil model with a total depth of 1.53 m (L255). As noted in our response to the previous comment, the soil moisture measurement at 0.15 m depth is used exclusively for comparison with the low-frequency DAS data, not with the dv/v results.

However, we realize that it is important to distinguish between the depth sensitivity discrepancy between CWI- and RPM-derived dv/v:

- The CWI-derived dv/v is shown in the sensitivity kernel (Fig. A2). The seismic waves are sensitive to changes in the entire near surface down to ~12 m, integrating the response of both the soil and the bedrock.
- The RPM-derived dv/v is simplified to a two-layer shallow soil model (extending to 1.53 m) because it's driven by our available soil moisture data. We lack data on moisture variations within the deeper weathered bedrock needed to extend this model further.

This difference in depth sensitivity directly explains why the RPM predicts much larger velocity changes than are actually measured by CWI. We have added the following discussion after L325 to clarify this important point.

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*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 more significant. 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.*

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- **Modeling dv/v under the rock physics framework:**

The manuscript outlines how effective elastic properties such as density and shear wave velocity are computed from effective stress, but it remains unclear how the effective stress is derived from the soil moisture profile. Could the authors clarify the exact steps used to convert volumetric water content and soil water potential into effective stress, especially given the complexity introduced by unsaturated versus saturated conditions?

Thank you for the question. We appreciate the opportunity to clarify them. The detailed theoretical background for this calculation is described in Section 2.2, beginning around line 72. The unified equation takes care of both saturated and unsaturated conditions.

To clarify our final calculation, we have 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):*

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

*where h=0.15 m is the measurement depth, $\rho_e$ is the effective density of the soil, calculated as $\rho_e = (1-\phi)\rho_s + \phi(\frac{VWC-\theta_r}{\theta_s-\theta_r}\rho_w + (1-\frac{VWC-\theta_r}{\theta_s-\theta_r})\rho_a)$ (Eq. 4). Here, the densities ($\rho_s, \rho_w, \rho_a$) and porosity ($\phi$) 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 $\theta_s$ is taken as the average of max(VWC) and $\phi$.*

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Additionally, what reference shear wave velocity model is used in the dv/v modeling? Is it the same velocity model derived from surface wave inversion in Section 5.1? If not, please explain the differences and justification.

In the RPM, the shear wave velocity is derived directly from Eq. 2 based on soil properties (e.g., effective stress). To calculate dv/v, we take the average of output shear wave velocity as reference. For CWI, it analyzes time shifts in the coda waves to directly calculate dv/v. We take the average waveform as reference to calculate the arrival time difference. Therefore, the resulting dv/v for both models are intrinsically aligned with respect to a mean state.

In Line 250, the authors state that the reduction in effective stress dominates during rainfall events. How is this conclusion supported within the model, especially considering that Figure 1 distinguishes suction stress behavior between unsaturated and saturated conditions? How are these different regimes handled in the dv/v modeling? A clearer explanation of how suction stress is represented and transitions across saturation states would help clarify the model's assumptions and limitations.

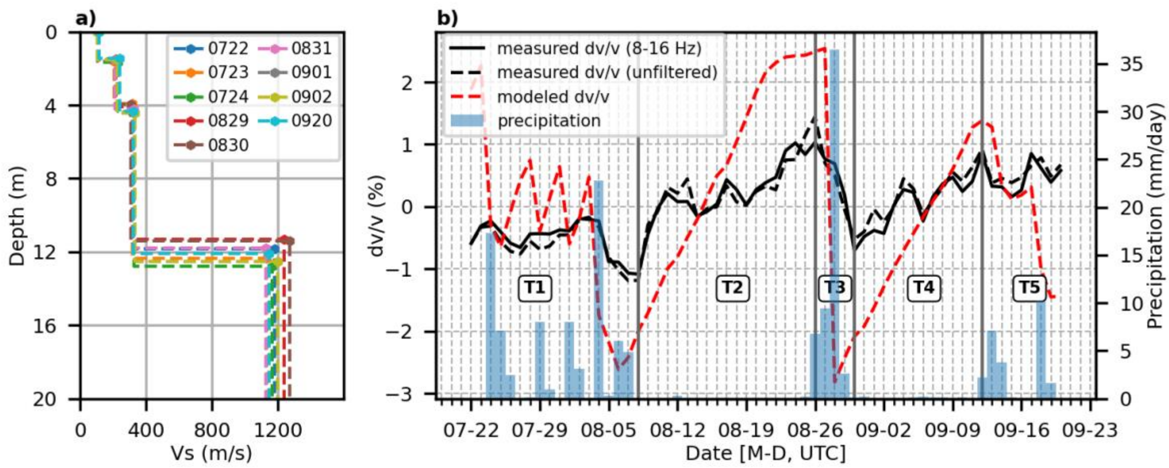
In this study, we used a unified equation to take care of both saturated and unsaturated conditions as shown in Eq. 1. Our modeling approach handles this transition continuously through the evolution of SWP. We do not need to switch between different equations for the two regimes. The explanation of how suction stress transits is presented at L85 in combination with Fig 1.

- **Figure 7a:** It is confusing to present temporal variation using full shear wave velocity models, as shown in Figure 7a, given that the observed changes are on the order of ~1%. This is well within the expected uncertainty of the inversion, which appears to be significantly larger. It does not seem reasonable to interpret such small variations as physically meaningful changes in the velocity structure based on these inversion results.

We believe the variations shown in Figure 7a are physically meaningful for the following reasons. First, although the *accuracy* of the inverted velocity model may be low, the *precision* of CWI is exceptionally high since this technique relies on coda wave interferometry rather than the inverted velocity model. Studies have demonstrated that sub-1% velocity changes can be reliably detected and interpreted (e.g., Brenguier et al., 2008; Shen et al., 2024). In our case, the strong coda wave arrivals give us confidence in the reliability of the observed velocity variations. Moreover, the temporal evolution of dv/v exhibits coherent patterns including distinct drops and recoveries in shear wave velocity that coincide with known soil moisture change.

- **Figure 7b:** What kind of smoothing or filtering was applied to the dv/v time series shown in Figure 7b? Could the apparent delay in dv/v response relative to precipitation events be an artifact of the smoothing process rather than a physical lag in the subsurface response?

Thank you for this thoughtful comment. We applied a bandpass filter (8-16 Hz). To demonstrate that the observed time lag is not an artifact of this bandpass filtering, we calculated the dv/v using the unfiltered daily stacked waveforms. As the plot below shows, the dv/v time series derived from both the filtered and unfiltered data show consistent behavior. This confirms that the lag is not an artifact of the data processing.




**Additional References:**

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