REVIEW REPORT FOR

# Seismic monitoring of landslide processes at the Hollin Hill Landslide

published in *Seismica*

---

## ROUND 1 REVIEWS

### REVIEWER 1

This paper as I interpret it has two main points: 1) to present and share the seismic datasets generated at the HHLO (hence it's later description in the Conclusion as a Data-based report), and 2) to describe some first interpretations of those data as a means to share observations and motivate future study. As a data report presenting the monitoring network and dataset I think this paper generally succeeds, although it needs to be more upfront with that aspect in the title and abstract to give readers a clear expectation on the purpose of the paper. As a report analyzing preliminary interpretations I think this paper needs more development. For example, the attribution of a certain harmonic signal to crack opening seems plausible but there is no accompanying data/observation/reference/model to support that interpretation so it comes off as purely speculative and unsupported. Meanwhile, sensor tilt is not described in the text until we arrive at that section, it's never mentioned how tilt is calculated and the results shown in 10^6 counts, and probably more could be learned by understanding tilt orientations for stations in the unstable/cracked area of the slope. And it has to be said both these observations as described really only relate to desiccation cracking, not strictly landslide processes. Generally I found the other interpretations similarly lacking of substantiation and detail, and suggest that this aspect of the paper needs further development. I'd really like to see the interpretations presented less as technique by technique and more centered around particular landslide phenomena. I have attached an annotated PDF that includes these and other comments.

(See annotated pages following this compilation of text comments.)

### REVIEWER 2

The manuscript presents a comprehensive study on the seismic monitoring of a slow-moving landslide at the Hollin Hill Landslide Observatory. The authors have made a significant effort in deploying a seismic network, collecting and analyzing data, and drawing preliminary conclusions. Overall, the paper has the potential to contribute valuable knowledge to the field of landslide research, but it also requires some improvements before publication. Here are my detailed comments:

- A more in-depth discussion of the limitations of existing methods and how the proposed seismic monitoring approach aims to overcome them would enhance the introduction. For example, the authors could elaborate on the specific challenges in interpreting geophysical signals and models related to landslide processes.

- The connection between the broader context of landslide hazards and the specific study at Hollin Hill could be strengthened. It would be beneficial to provide more global statistics or examples of landslide impacts to emphasize the significance of the research.

- It would be useful to include more information about the spatial extent of the landslide and the distribution of different geological units across the site. This could help readers better understand the variability in the subsurface conditions and its potential impact on the seismic monitoring results.

- The discussion of previous research at the HHLO could be organized more clearly. For example, presenting the key findings from geoelectrical monitoring and other studies in a tabular format could make it easier for readers to follow the evolution of research at the site and the relationships between different monitoring methods.

- The description of the YJ network deployment is clear, but it would be beneficial to provide more information about the selection criteria for the specific sensor locations. Were there any pre-existing data or models that guided the placement? How were the "undisturbed," "dormant," and "active" areas defined, and what was the expected impact of these different zones on the seismic data?

- The discussion of sensor failures and data coverage is important. It would be helpful to include more details about the attempts to diagnose and address the issues with the failed sensors. Additionally, a more comprehensive analysis of the potential impact of the reduced data coverage from the failed sensors on the overall results and conclusions could be provided. For example, could the missing data from certain stations introduce biases in the event analysis or the interpretation of spatial patterns in the seismic response?

- The discussion of noise sources could be expanded. In addition to the identified farming and highway noise, it would be interesting to explore whether there are any other potential sources of noise, such as nearby industrial activities or natural sources like wind. A more detailed analysis of the noise characteristics in different frequency bands and how they vary over time could also provide valuable insights. For example, are there any diurnal or seasonal patterns in the noise levels that could affect the interpretation of the seismic data?

- The application of STA/LTA filters and the detection of seismic events are well-described. The identification of a signal potentially related to landslide activity is interesting. However, more evidence could be provided to support this claim. For example, could the authors perform a more detailed spectral analysis of the signal to further characterize its frequency content and compare it with known seismic signatures of landslide processes? Additionally, it would be useful to investigate whether the occurrence of this signal correlates with other observable changes at the landslide, such as changes in slope displacement or soil moisture.

- The analysis of tilt data and its relationship with soil moisture and matric potential is a valuable contribution. The figures effectively illustrate the trends in tilt and the comparison with other parameters. However, it would be beneficial to discuss the possible mechanisms underlying the observed relationship in more detail. For example, how does desiccation cracking exactly affect the sensor tilt, and what are the implications for the interpretation of slope deformation? Are there any other factors that could potentially influence the tilt measurements, and how were they accounted for?

- The approach for computing the H/V ratio and the analysis of temporal spectrograms are clear. The identification of seasonal variations in secondary peaks and their relationship with perched water tables and impedance contrast is interesting. However, further interpretation of these findings in the context of the overall landslide behavior could be provided. For example, how do these changes in the H/V ratio relate to the stability of the landslide? Could the authors use the H/V ratio data to infer any changes in the subsurface structure or material properties?

- The ambient noise cross-correlation analysis is promising, but the results could be presented in more detail. The link between soil moisture and velocity change is demonstrated, but a more quantitative analysis of the relationship would be beneficial.

- The discussion section effectively summarizes the main findings and their implications. The recognition of the challenges related to sensor tilting, noise, and source location analyses is important. However, the proposed solutions, such as deploying more robust sensors, could be further explored. What are the specific advantages and disadvantages of different types of seismic sensors in this context, and how would they address the identified issues? Additionally, a more comprehensive discussion of the potential limitations of the current study and how they could impact the generalizability of the results would be valuable.

Overall, the manuscript requires some revisions to improve the clarity and depth of the presentation. The authors should address the specific comments provided above to enhance the scientific rigor and value of the study.

Answers to these reviews are inserted below, following this compilation of text comments.

---

## ROUND 2 REVIEWS

### REVIEWER 1

I thank the authors for their detailed response to my previous comments. I agree that it is difficult to find the right balance between presenting a dataset and offering robust and interesting first interpretations of that dataset, and I think the revised manuscript is a strong step forward in the right direction toward that balance. The figures, presentation and overall analysis are much improved. As I am satisfied with the author’s response to the reviewer comments, I had a look at the manuscript freshly again and offer some final suggestions for improvement. I think the manuscript is in excellent shape and can proceed with only minor final corrections. Please see the attached annotated PDF for all comments.

See annotated pages following this compilation of text comments.

REVIEWER 2

After reading the manuscript and the authors’ responses to the first-round reviewer comments, I think the authors have addressed the raised issues and the corresponding revisions made to the manuscript. I have no further comments to add. However, to enhance readability and help readers quickly locate the key study area, it would be nice if the landslide boundary could be clearly plotted and labeled in Figure 1a.

Answers to these reviews are inserted below, following this compilation of text comments.

---

# Seismic monitoring of landslide processes at the Hollin Hill Landslide Observatory

A. Watlet[1^,2], J. Whiteley[1^,3], B. Dashwood[1], D. Morgan[1], V. Lane[4], L. Finch[4], D. Gunn[1*], T. Lecocq[5], J. Chambers[1*]

[1]Shallow Geohazards and Earth Observation, British Geological Survey, Nottingham, United Kingdom
[2]Geology and Applied Geology, University of Mons, Mons, Belgium
[3]Ground Engineering & Tunnelling, AtkinsRéalis, Bristol, United Kingdom
[4]SEIS-UK, University of Leicester, Leicester, United Kingdom
[5]Seismology - Gravimetry, Royal Observatory of Belgium, Belgium, Brussels, Belgium
^Honorary Research Associate of the British Geological Survey
*Retired
[*]Corresponding author: arnw@bgs.ac.uk

## Author ORCIDs

A. Watlet: 0000-0003-0318-9032
J. Whiteley: 0000-0001-5254-4817
B. Dashwood: 0000-0002-8396-861X
V. Lane: 0000-0002-9156-114X
T. Lecocq: 0000-0002-4988-6477
J. Chambers: 0000-0002-8135-776X

## Author contributions

Conceptualization: A. Watlet, J. Whiteley
Data Curation: A. Watlet, J. Whiteley
Formal Analysis: A. Watlet
Funding Acquisition: J. Chambers, D. Gunn, T. Lecocq, A. Watlet, J. Whiteley
Investigation: B. Dashwood, D. Morgan, A. Watlet, J. Whiteley
Methodology: A. Watlet, J. Whiteley
Project Administration: V. Lane, A. Watlet, J. Whiteley
Resources: V. Lane, L. Finch
Software: A. Watlet, T. Lecocq
Supervision: J. Chambers
Visualization: A. Watlet
Writing – original draft: A. Watlet, J. Whiteley
Writing – review & editing: A. Watlet, J. Whiteley

The first two authors contributed equally to the production of this study.

## Abstract

Early-warning of landslide failure relies on understanding subsurface processes that drive slope destabilisation. Heterogeneity in landslide systems causes spatiotemporal variation in these dynamic processes, which are typically driven by changes in moisture content or mechanical behaviour. There is therefore a need to develop methods that can ~~observe~~ and measure changes in the subsurface to inform stability. Seismic monitoring, ~~through the use of sensors deployed to the landslide surface~~, can record information on the elastic behaviour of the ground in response to immediate and long-term processes such as slope displacement and moisture variation respectively. Here, we report on ~~the deployment of~~ a seismic network deployed at a slow-moving clay-rich landslide in North Yorkshire UK, representative of many landslides in clay-rich lowland slopes. The temporary network was ~~deployed~~ for two years with the aim of understanding how the seismic response varies between sensors ~~deployed to parts of the landslide~~ with distinctly different hydrogeological properties. We present an overview of the rationale and deployment procedure, as well as a preliminary ~~analysis~~ of data quality, event analysis, tilt observations, H/V ratio calculations and ambient noise cross-correlation. We ~~conclude~~ that ~~the~~ moisture dynamics of the slope have a significant influence on ~~the~~ observed data, ~~and make further recommendations for the analysis of the dataset~~.

## Résume (French)

La détection précoce des glissements de terrain repose sur la compréhension des processus souterrains qui conduisent au déclenchement des évènements. L’hétérogénéité structurelle des glissement de terrain peut entrainer une variabilité spatio-temporelle de ces processus dynamique qui est souvent due à des changement d’humidité ou de comportement mécanique. Il est donc important de développer des méthodes permettant une meilleure observation de ces changement dans le sous-sol pour évaluer la stabilité des pentes. La surveillance sismique, par l’utilisation de capteurs déployés à la surface du glissement de terrain, peut permettre d’enregistrer des informations sur le comportement élastique du sol, en réponse à des phénomènes tels que les déplacements en surface et les variations d’humidité. Nous décrivons ici le déploiement d’un réseau sismique sur un glissement de terrain argileux à déplacement lent dans le North Yorkshire, au Royaume-Uni, représentatif d’un grand nombre de glissements de terrain argileux dans le monde. Le réseau temporaire, déployé sur une durée de 2 ans, avait pour but de comprendre comment la réponse sismique varie dans des zones du glissement de terrain aux propriétés hydrogéologiques différentes. Nous présentons un aperçu de la procédure de déploiement, ainsi qu’une analyse préliminaire des données, de l’analyse des évènements, des observations de tilt, des calculs de rapport H/V, et de la corrélation croisée du bruit ambiant. Les premières conclusions indiquent que les données observées sont significativement influencées par la dynamique de l’humidité du sol de la pente, et nous permettent de formuler des recommandations pour l’analyse du jeu de données.

## Non-technical summary

Early warning of landslides is important for safety, and it depends on understanding what happens underground that causes slopes to become unstable. Landslides, especially those that have a lot of clay and move slowly, vary a lot because of differences in moisture and how the ground behaves. Therefore, we need good methods to observe and measure these changes. One way to do this is ~~by using~~ seismic monitoring. ~~This~~ involves placing sensors ~~called seismometers (which~~ measure ~~earth~~ vibration~~s)~~ on the surface of ~~the~~ landslide to track how the ground moves and responds over time, especially to changes in moisture. We set up a network of these sensors at a slow-moving landslide in North Yorkshire, UK. The goal was to see how the seismic readings differed in areas with different water and ground properties. We explain why and how we set up the sensors, and give an initial ~~look~~ at the data we collected. Our findings show that changes in moisture significantly affect how the ground responds, and how landslide activity can generate specific vibrations. Finally, we offer suggestions for further analyses.

# 1. Scientific background and motivation

## *1.1 Introduction*

Landslide hazards impact population safety and infrastructure ~~condition~~ across the globe. The risk of landslides can be mitigated through engineering interventions or management, with the latter often favoured due to lower costs. One such method of landslide management is the implementation of an early-warning system that uses field observations to warn of impending slope failure events, thus allowing time for more efficient intervention planning or removal of the elements at risk (Intrieri et al., 2012). Slope-scale early warning systems typically tend to rely on observations of rainfall, ground moisture, or slope displacement to predict future failure events.

In recent years, geophysical techniques have been increasingly used for slope monitoring (Whiteley et al., 2019). Geophysical techniques offer unique advantages in that they can ~~often~~ obtain measurements from across large areas of the subsurface (unlike point sensors) and are able to infer processes occurring at depth within a landslide body (unlike surface observations). However, the sensitivity of geophysical methods to proxies, rather than direct measurements, of subsurface ground conditions means there can be ambiguity in interpreting the spatial and temporal variation in geophysical signals and models (Le Breton et al., 2021).

Here, we present ~~the~~ initial findings from a deployment of seismometers (the YJ 2020-2023 temporary network) at a slow-moving, clay-rich landslide in North Yorkshire, UK, in an effort to encourage further, more advanced investigations on the acquired dataset. Seismic monitoring is identified as a complementary technique to the systems already deployed at the site, which have largely focused on understanding soil moisture dynamics (Uhlemann et al., 2016). Monitoring using a network of seismometers has the advantage of providing time-continuous measurements from the site, as well as providing measurements of the mechanical properties of landslide materials.

### *1.2 Site description*

The Hollin Hill Landslide Observatory (HHLO) is a field observatory and laboratory that has been operated by the British Geological Survey (BGS) since 2008. The site has been important in the research and development of ~~novel~~ geophysical, geotechnical and remote sensing technologies for the observation and monitoring of natural landslide processes. The Hollin Hill landslide is a slow moving, clay-rich landslide, which is seasonally reactivated when soil moisture increases in winter (Uhlemann et al., 2017). In summer it experiences ~~high~~ shrinkage and surface fissuring, which may consequently impact the hydrological regime of the landslide in following years. The HHLO is representative of many landslide hazards in clay-rich lowland slopes worldwide, with the underlying Lias Group rocks accounting for 15% of all landslides in the UK (Hobbs et al., 2012).

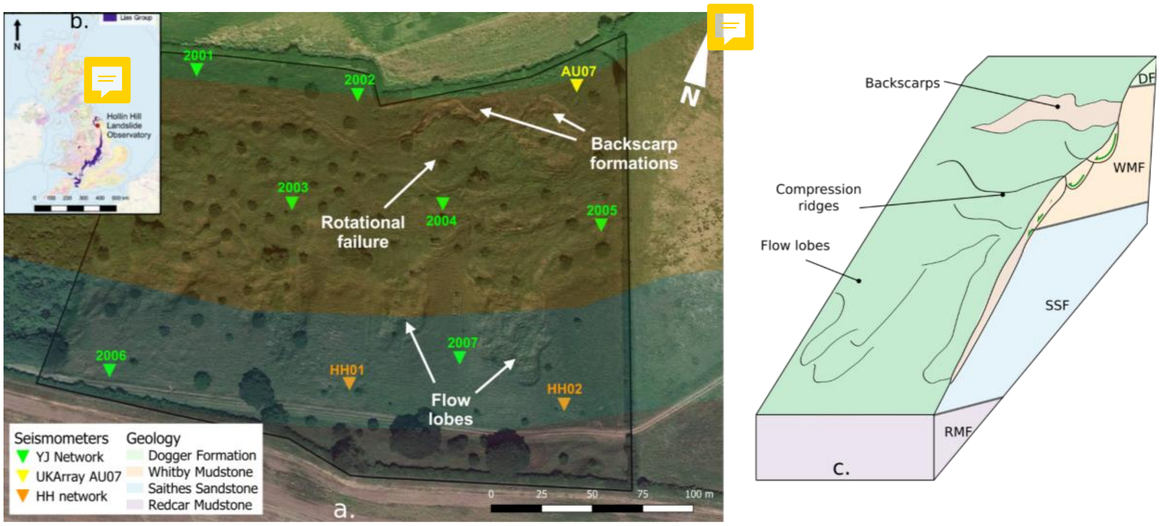


**Figure 1. a**) Map of the HHLO with major geomorphological features, underlying geology and seismometer locations. **b**) Location of the HHLO relative to Lias formations in the UK. **c**) Schematic cross-section of the geological layers and main landslide features.

The HHLO is located on a south facing slope which comprises a series of interbedded, north-dipping, shallow marine mudstones and sandstone, comprising (in descending order) the Dogger Formation (DF), which is a limestone and sandstone unit acting as a minor aquifer, the Whitby Mudstone Formation (WMF), the Staithes Sandstone Formation (SSF), and the Redcar Mudstone Formation (RMF) (Chambers et al., 2011). The WMF is the main unit prone to failure. The top of the slope exhibits rotational failures in the WMF leading to the formation of ~~several~~ prominent backscarps, the most recent of which has been developing since 2016 (Boyd et al. 2021). The landslide failure mode becomes translational ~~displacement~~ mid-slope, with some large flow lobes of mudstone materials creeping on top of the SSF toward the base of the slope (Figure 1).

Research at the HHLO over the past two decades has primarily focused on ~~the~~ development of geophysical systems for monitoring slope processes to enhance early-warning capability ~~of slope failure~~ (Whiteley et al., 2019, Whiteley et al. 2021), with a particular focus on understanding ~~the~~ spatiotemporal variation in moisture dynamics driving slope destabilisation (Chambers et al, 2021). Key findings from geoelectrical monitoring at the HHLO include: i) estimating spatiotemporal variation in key material properties such as moisture content (Merritt et al., 2013) and matric potential (Boyd et al., 2024) can be achieved using geophysical-geotechnical petrophysical relationships, ii) slope displacements typically occur once a threshold of ~48% gravimetric moisture content (GMC) is reached (Uhlemann et al., 2016), and iii) changes in electrode positions can be used to recover slope movements from geoelectrical monitoring datasets (Wilkinson et al., 2016). Geoelectrical monitoring of subsurface moisture has been supported by studies also looking at corresponding slope displacements from point sensors (Uhlemann et al., 2016), UAV surveys (Peppa et al., 2019), GPS time-series (Boyd et al., 2021) and InSAR measurements (Kelevitz, 2022).

More recently, seismic methods have been used to better understand how moisture dynamics influence the mechanical behaviour of saturated soils preceding failure. Whiteley et al. (2020) compared changes in seismic velocity from time-lapse active seismic refraction surveys with ground moisture and local rainfall data ~~and found~~ that variations in the elastic properties of the sliding layer ~~of the HHLO materials~~ are linked to saturation levels (Whiteley et al., 2020). A conclusion of this study was that while repeated active surveys can provide insight into the saturation-driven mechanical variations at the HHLO, their implementation is impractical for long-term use. Hence, passive seismological monitoring has been identified as a potentially viable option for long-term monitoring of slope processes, as ~~already~~ demonstrated on other slow-moving landslides (Fiolleau et al., 2020; Mainsant et al., 2012; Tonnelier et al., 2013; Walter et al., 2012).

Whiteley et al. (2018) presented preliminary results from a period of seismological monitoring at the HHLO from a sparse network of three broadband seismometers, comprising two Nanometrics Trillium 120 seismometers (University of Bristol; not currently archived, local station IDs HH01 and HH02) and a Güralp CMG-3ESP (British Geological Survey; network UR 2015 - present, station ID AU07).

### *1.3 The YJ temporary network*

The YJ (2020-2023) network, ~~which will~~ subsequently be referred to as YJ, consists of seven Güralp 6TD sensors deployed at the HHLO between March 2020 and March 2022 ~~as part of a~~ loan from the UK’s Natural Environment Council (NERC) Geophysical Equipment Facility (GEF) (Brisbourne, 2012). The YJ network allows us to test the hypothesis that seismometer setting, e.g., ~~siting seismometers~~ on different landslide domains~~,~~ comprising areas with different failure mechanisms (i.e., translational/creep) and underlying geology (i.e., WMF/SSF) (Table 1) will have an influence on the single-station analysis of seismological data, providing landslide domain characterisation and monitoring ~~using~~ passive ~~seismic~~ data. Additionally, the YJ network was designed to test the hypothesis that changes in relative surface-wave velocity, derived through cross-correlation of ambient noise, can be used to detect variations in shear strength of landslide materials, which is critical for early-warning of slope failures.

**Table 1.** Properties of the station locations in terms of geology and landslide domain at the HHLO.

| ID | Latitude | Longitude | Elevation | Location | Geological ~~setting~~ | Landslide domain |
|---|---|---|---|---|---|---|
| 2001 | 54.11137 | -0.961835 | 100.9 | Crest | WMF | Undisturbed (above movement zone) |
| 2002 | 54.111449 | -0.96061 | 98.7 | Crest | WMF | Undisturbed (above movement zone) |
| 2003 | 54.110912 | -0.960868 | 85.9 | Mid-slope | WMF | Dormant (no active movement at time of monitoring) |
| 2004 | 54.111074 | -0.959778 | 86.7 | Mid-slope | WMF | Highly active (located beneath active rotational failure) |
| 2005 | 54.111074 | -0.959778 | 86.7 | Mid-slope | WMF | Partially active (located beneath recent rotational failures) |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2006 | 54.11118 | -0.958567 | 82.1 | Toe | SSF | Undisturbed (below movement zone) |
| 2007 | 54.109977 | -0.96187 | 59.6 | Toe | SSF | Undisturbed (between active flow lobes of landslide) |

## 2. Instrument deployment

The seven Güralp 6TD seismometers were deployed between 9 and 11 March 2020 following the SEIS-UK deployment procedure (Lane et al., 2020). The seismometers were buried 40 cm below ground level in a pit filled with sand. Each station was powered by a 12V battery installed in a metal box recharged by ~~2 x~~ 20W solar panels mounted on a wooden frame. The metal box was customised by BGS to allow the connection of two lengths of hose via plastic push-fit connectors into the storage box. This provided extra protection for the cabling from livestock and moisture ingress (Figure 2).

The 6TDs were configured to record at 200 ~~sps.~~ With this configuration, the ~~6TDs~~ could store up to four months of data. Eight service runs were completed on schedule, with the exception of one run in Spring 2021 which was delayed due to the impact of Covid-19 on staff availability (Figure 3). This service run was conducted a few days after the data storage disks reached capacity. Details of activities during deployment, on each service run and during decommission were recorded on service sheets, which were scanned and archived.

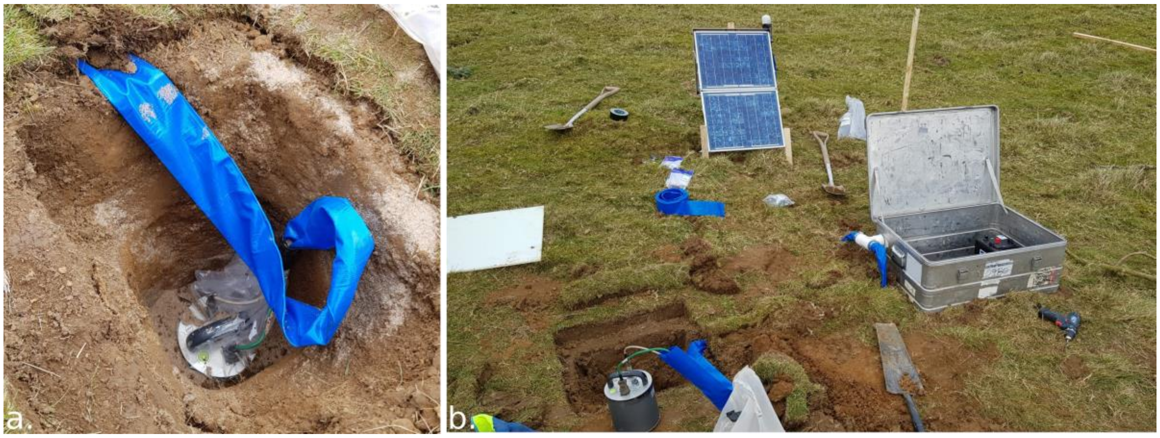


**Figure 2.** **a**) Typical 6TD installation at the HHLO site. **b**) Wider station setup showing solar panels and customised storage box for housing battery, data disk and cable connection box.

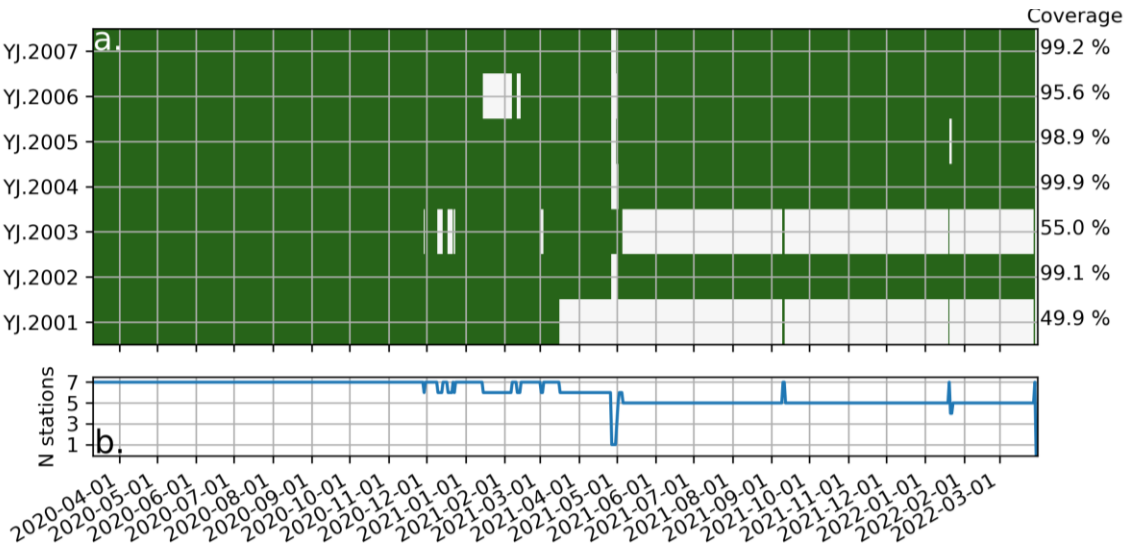


**Figure 3. a**) Data availability per station. **b**) Number of stations available per day.

One seismometer (YJ.2004) failed during the deployment due to extensive subsurface flooding of the installation, and a replacement sensor was provided by SEIS-UK. Two stations (YJ.2001 and YJ.2003) had persistently failed shortly after service runs, with issues commencing in winter and spring 2021 respectively. These issues were associated with blown fuses, although no exact cause ~~for this~~ was determined ~~with absolute certainty~~, ~~but~~ moisture reaching the electronic boards was suspected. Neither station was able to record data for significant lengths of time after these dates. Five of the seven 6TDs had >95% data coverage, with network-wide data coverage being 85% for the two-year monitoring period.

## 3. Description of obtained data

### *3.1 Repository details*

~~D~~ata are archived on the SEIS-UK Octomore data management system and IRIS data management centre with network code YJ 2020 - 2023 (Watlet et al., 2020a), under the name of Yorkshire Landslide Observatory (YoLO). According to the SEIS-UK guidelines, access is restricted until March 2025 on the IRIS repository, but specific access can be arranged upon request until then.

### *3.2 Data quality and noise level*

The quality of recorded data is good, with the secondary microseism being closer to the high model of Peterson (1993), as can be expected on an island such as Great Britain (Figure 4).

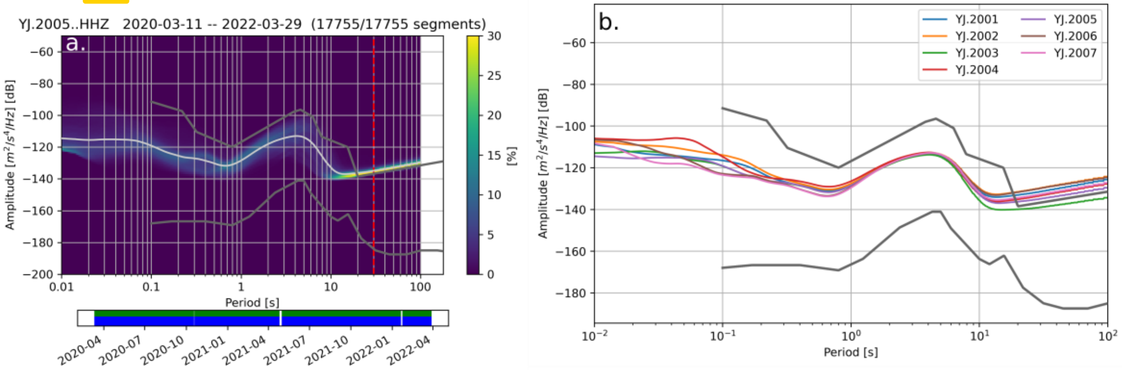


**Figure 4. a**) Vertical component PPSD plot for the monitoring period for station YJ.2005. Grey lines indicate the low and high noise models of Peterson (1993), the red line marks the upper period bound of the 6TD response (30s). **b**) Average PPSD for each station.

The HHLO site is relatively remote, located in a rural area approximately 20 km away from the closest city, York. Higher frequency noise is mainly influenced by farming activity, and especially the presence of sheep in the field, and to a smaller extent to a highway passing ~7 km south-east. The farming source of the high frequency noise is evidenced by significant increases in noise intensity in the breeding season (Figure 5), which presents an interesting but challenging noise source to consider in the processing steps.

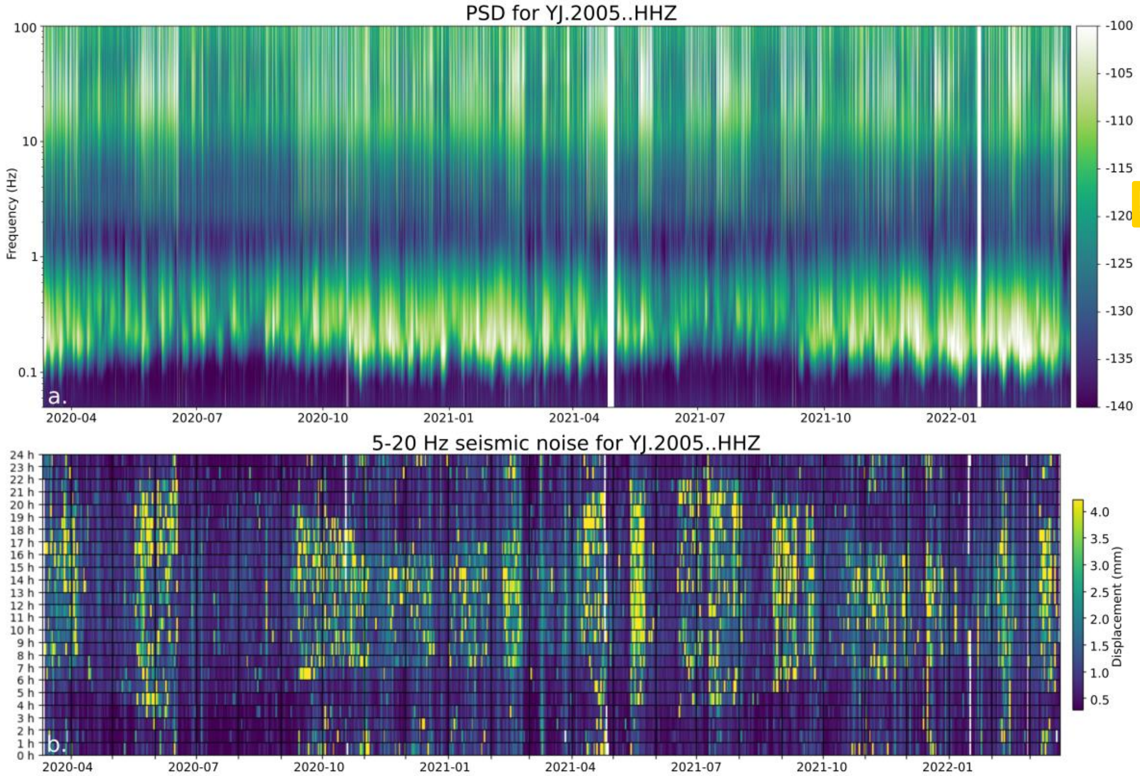


**Figure 5. a**) Spectrogram of ambient noise over time compiled from hourly averaged PSD for YJ.2005. **b**) Temporal evolution of high-frequency (5 to 25 Hz) ambient noise displayed as a matrix plot. Each row corresponds to an hour of data (produced using SeismoRMS by Lecocq et al., 2020). Higher frequency noise is linked with sheep presence in the field.

## 4. Preliminary interpretations

### *4.1 Seismic event analysis*

We applied a series of classic STA/LTA (short-term average/long-term average) filters on the YJ network inventory and detected a range of seismic events, of which some have a local source (Watlet et al., 2020b). Amongst events attributed to local environmental noise sources (farming activities, livestock on site, etc.), one signal is thought to be more clearly related to the landslide activity (Figure 6). This event type, usually recorded on several of the stations, was observed on various occasions (> 100 occurrences), mainly in dry conditions. It has a short duration (<2 s) and shows harmonic-like frequency components (in the 7-25 Hz band), which may indicate the opening of fractures during periods of clay-shrinkage.

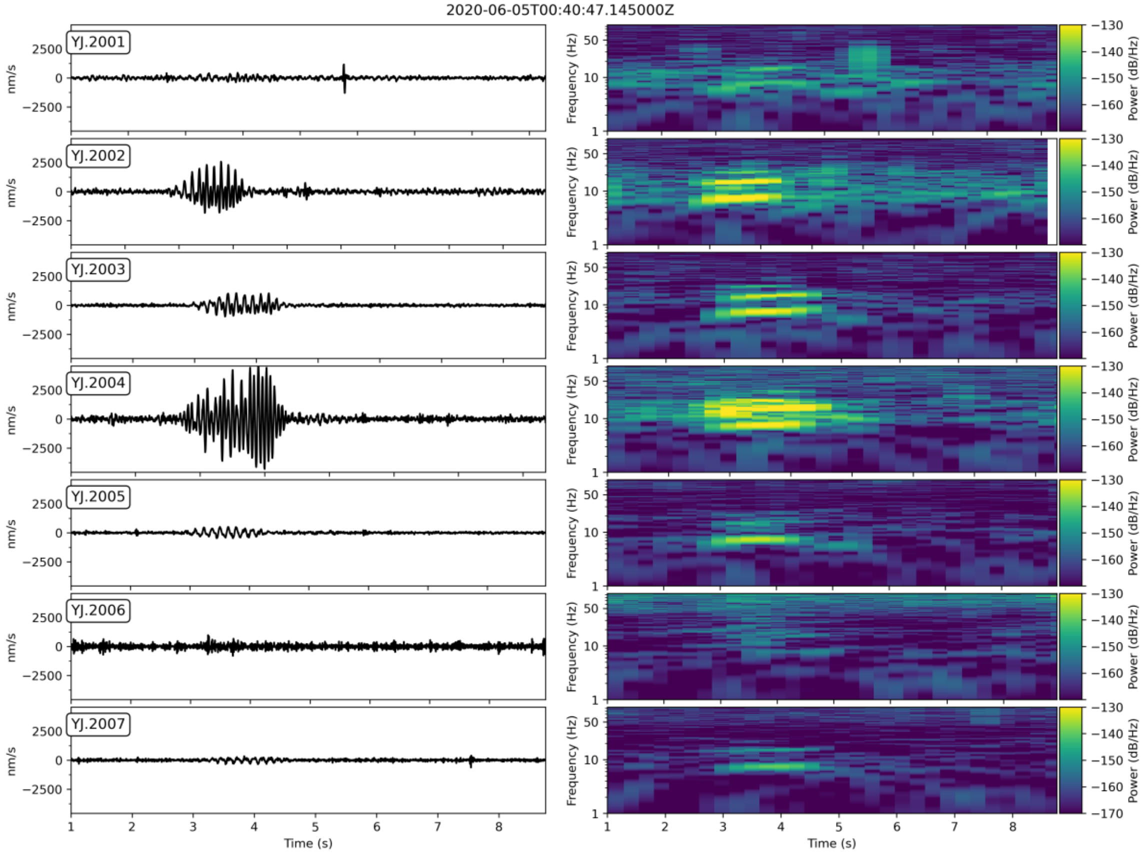


**Figure 6.** Left: Example seismic events from crack generation with vertical component traces. Right: Accompanying spectrograms.

### *4.2 Tilt*

In the landslide context, looking at tilt from the internal masses of the seismometers may provide insightful information on the slope deformation. Individual sensor tilts in the E and N components can be seen to occur to a greater degree between May and October 2020, which are typically regarded as drier months at the HHLO (Figure 7). By early 2021, several soil suction sensors measuring the matric potential of the soil were installed at the HHLO. Comparison of the tilt with the matric potential in 2021 shows a transition from slow but continual drift in tilts to more rapid and dramatic variations in tilt at times of higher matric potential. This indicates the possible influence of desiccation cracking on sensor stability at the HHLO.

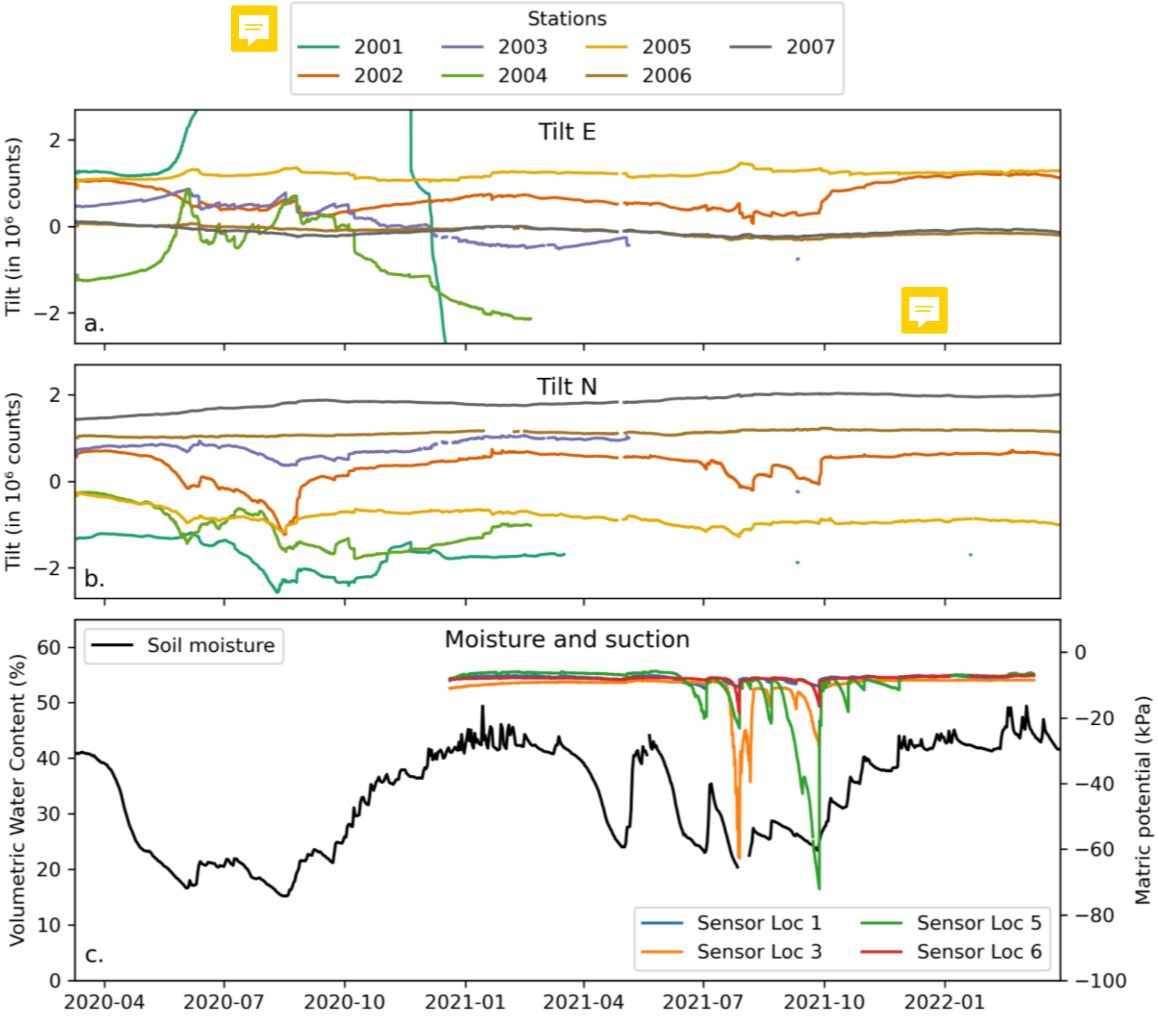


**Figure 7.** Tilt along E (**a**) and N (**b**) components for all stations of the YJ network, compared with matric potential at 4 locations (data starting in November 2021) and soil moisture from the COSMOS-UK station at Hollin Hill (**c**).

### *4.3 Continuous H/V observations*

We ~~developed an approach to compute~~ temporal H/V ratios (Nakamura, 1989) based on the ratios between hourly power spectral density (PSD) spectrograms of the horizontal and vertical components, in a similar way as van Ginkel et al. (2024). The H/V ratios *a* are ~~computed~~ as follows:

$$a = \frac{\frac{\sqrt{10^{\frac{E}{10}}}+\sqrt{10^{\frac{N}{10}}}}{2}}{\sqrt{10^{\frac{Z}{20}}}} \text{ (Eq. 1)}$$

Where *E*, *N* and *Z* are the hourly PSD expressed in dB for the east, north and vertical components respectively.

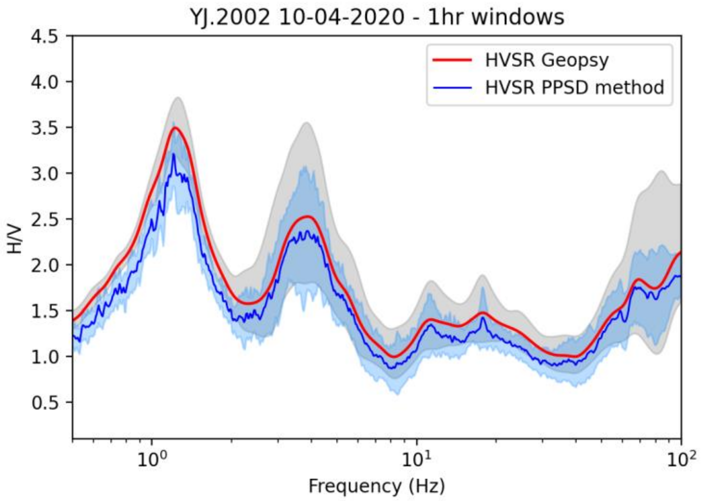


**Figure 8.** Comparison between HVSR computed using Geopsy software (Wathelet et al., 2020) and the PPSD ratio method for station YJ.2002 for 10-04-2020.

Figure 8 shows that our approach delivers similar H/V plots as those computed with the Geopsy software (Wathelet et al., 2020) for a 1-hour time window. Temporal H/V spectrograms ~~consist of displaying~~ the temporal evolution of hourly H/V plots. They ~~inform~~ on the stability and ~~frequency~~ shifts of major and minor frequency peaks (Figure 9). Temporal H/V spectrograms are useful to study the subsurface changes underneath each station. On the YJ network dataset, we have found that some of the secondary peaks appear seasonally (e.g. in the 10-25 Hz frequency band for YJ.2002), which can be related to the occurrence of temporary perched water tables in winter, or increased impedance contrast in summer between relatively drier mudstone and wetter underlying sandstone. Investigating the noise source is required to draw further interpretations. Data for some of the stations also experience shifts in the secondary peak frequency (e.g. in the 18-22 Hz frequency band for YJ.2005) which are linked to shear wave velocity variations in the upper layers due to change in moisture content, as identified in a different slope context by Guo et al. (2023). The fact that such shifts are present on data from YJ.2005 and not as clearly on YJ.2002 could be linked to their respective locations on the landslide. YJ.2005 is sited on the reworked WMF mudstone materials, which ~~are~~ experienc~~ing~~ larger amplitudes in wetting and drying seasonal ~~processes~~ than for SSF sandstone materials within which YJ.2002 sits. These velocity variations are also investigated via ambient noise cross-correlation.

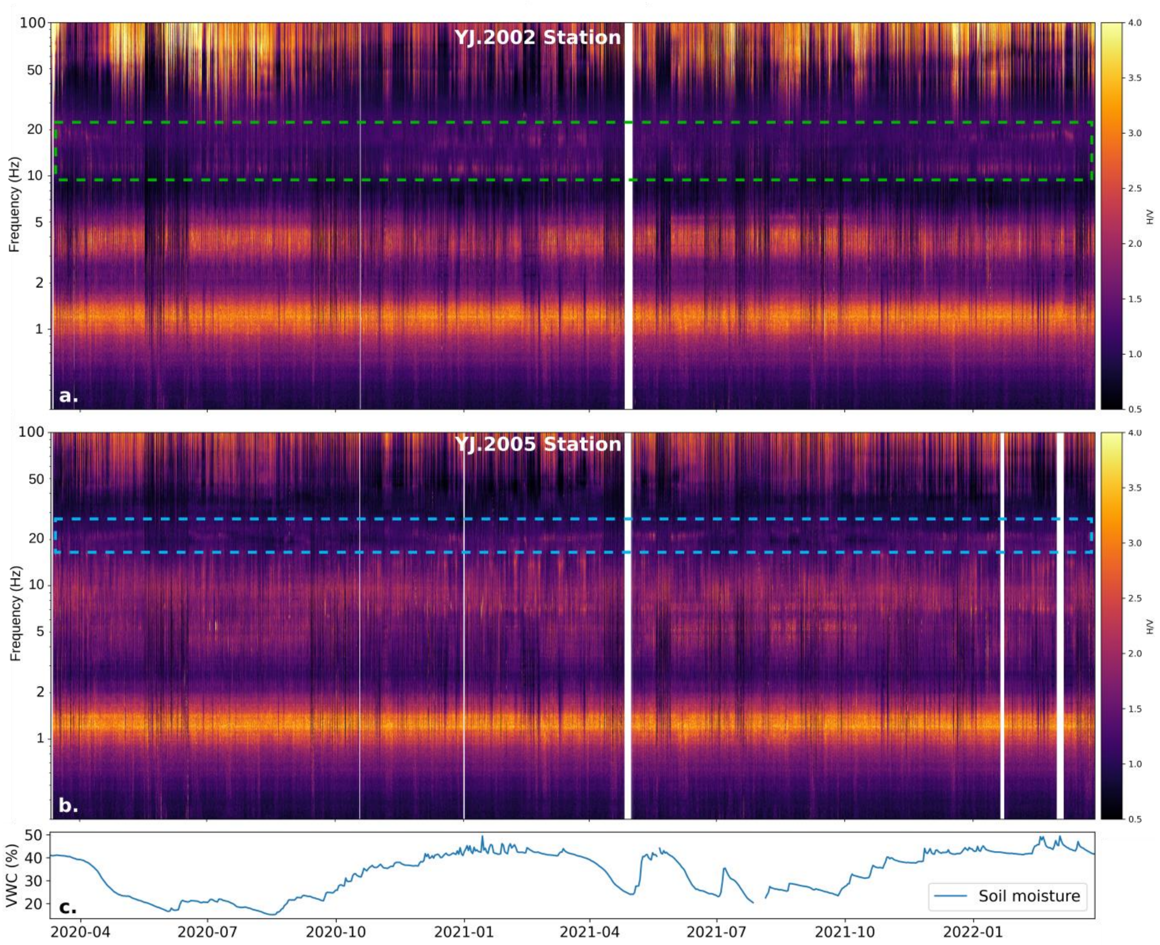


**Figure 9.** Spectrogram of HVSR over time for station YJ.2002 (**a**) and YJ.2005 (**b**), as well as soil moisture recorded at 10 cm by the COSMOS-UK station at Hollin Hill (**c**). Green and blue dashed boxes highlight frequency bands 10-20 Hz and 18-22 Hz respectively.

### *4.4 Ambient noise cross-correlation and velocity change*

Ambient noise data were processed with MSNoise (Lecocq et al., 2014), broadly following the steps described by (Bensen et al., 2007). Hourly seismograms were split into 60s long segments which were cross correlated between each possible pair (21 pairs when all stations were recording) for the ZZ, EE and NN components. The cross-correlations were stacked for each day. The seismic velocity change was computed following the moving window cross-spectral (MWCS) technique (Clarke et al., 2011) on the coda of the cross-correlations. Seismic velocity changes (*dv/v*) are derived from relative travel-time variations (dt/t) detected in a sliding window of the coda wave.

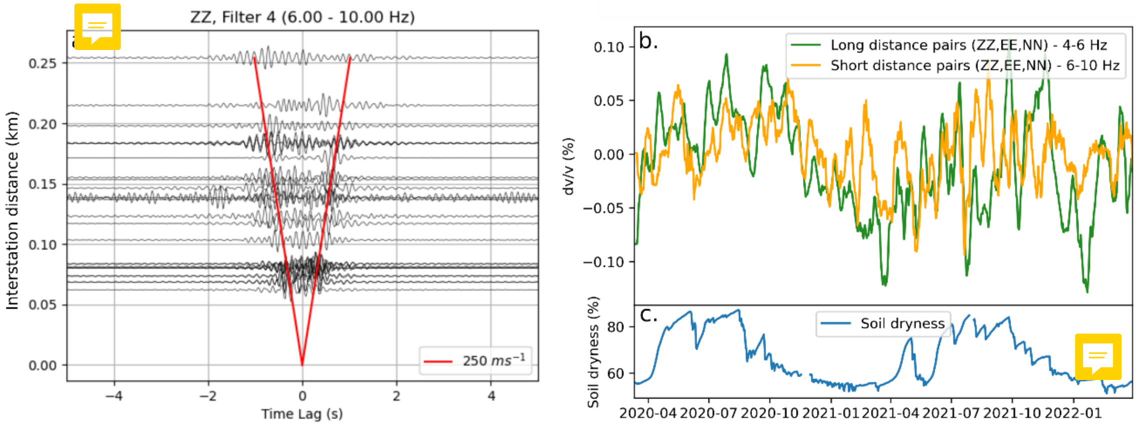


**Figure 10. a**) Average cross correlation functions for each pair displayed as a function of the interstation distance (for the 6-10 Hz band). **b**) Example *dv/v* plot for long distance (> 150 m) and short distance (< 150 m) pairs at two selected frequency bands. **c**) Soil dryness (inverse of soil moisture).

Preliminary results on specific frequency bands suggest a link between soil moisture and velocity change (Figure 10), with velocity decreasing as soil dryness decreases. Further analyses on a broader range of frequency bands should be considered following the approach presented ~~in~~ (Oakley et al., 2021). These further analyses could include rotation into a coordinate system aligned with the local surface slope, because high-frequency surface waves are expected to follow the surface topography.

### *4.5 Discussion of preliminary observations*

Wetting and drying processes within clay materials ~~are driving~~ landslide activity and slope displacement at Hollin Hill. Our observations suggest that changes in soil moisture~~,~~ and pore water pressure at shallow depth ~~are~~ impact~~ing the~~ seismic signals recorded by the YJ network. Clay shrink~~ing~~ associated with decreasing water content generates tilt on the horizontal masses of the seismometers. Desiccation and large crack openings seem to generate specific seismic events, some of which are recorded throughout the network. Conversely, temporal HVSR spectrograms indicate that secondary H/V peaks ~~are subject to~~ vary both in frequency and intensity as impedance contrasts and seismic velocities fluctuate in the shallow subsurface due to change in soil moisture and the occurrence of seasonal perched water tables. Seismic interferometry has also been trial~~l~~ed on data from the network and ~~also~~ highlights changes in seismic velocities in medium to high frequency bands, likely linked to changes in soil moisture.

Overall, our preliminary observations suggest that, upon further investigations, seismic records from the YJ network have the potential to shed new light on the link between landslide activity and seismic activity on clay-rich, slow moving landslides. Challenges related to tilting sensors, anthropogenic (and sheep) noise variations, as well as source noise location analyses need to be addressed in order to further determine the reliability of the data throughout the monitoring period. However, some limitations could be overcome by deploying more robust seismic sensors, such as seismic node arrays or a new generation of seismometers less sensitive to tilt (e.g., Reis et al., 2021).

## 5. Conclusions

From March 2020 to March 2022, we operated the YJ network composed of seven Güralp 6TD seismometers, provided by SEIS-UK, at the HHLO to monitor landslide processes. This dataset has demonstrated the potential for the application of approaches typically applied to monitoring large-scale geohazards (volcanoes, earthquakes, etc.) to investigate shallow, hydrologically controlled landslide ~~processes.~~ These investigation approaches include i) the use of seismic event detection (STA/LTA filters) to identify crack generation during dry summers, ii) seasonal tilt observations, iii) determination of continuous H/V profiles to monitor changes in ~~peak~~ resonance frequenc~~y~~ associated with hydrologically controlled impedance contrasts and velocity changes, and iv) ambient noise cross-correlation to obtain broad changes in near-surface velocity associated with soil wetting and drying ~~processes.~~ Although the analysis of data from this network is preliminary, ~~it is clear~~ that the soil moisture dynamics influence the mechanical behaviour of landslide-prone materials at the site, an observation consistent with those made in other recent studies (e.g., Watlet et al., in preparation; Whiteley et al., 2020; Ouellet et al., 2024).

One main motivation of this data-based report was to present the seismic dataset and highlight the potential for further investigations by ~~enthusiastic~~ fellow seismologists. These may include AI-based approaches to detect microseismic events generated by landslide activity. The tilt signals measured by the seismometers have shown their potential to investigate slope-scale seasonal shrink-swell processes and could be used in combination with other slope deformation sensors and techniques to further validate the observations and the implications on landslide activity. The temporal H/V analyses are ~~quite~~ promising and could be combined with analyses on azimuthal dependence and temporal variability in the secondary peak frequencies for instance to investigate potential links of resonance direction and slip surfaces, in a similar way as in Guillemot et al. (2024). Looking at the inverse of HVSR (VHSR) could also be considered to improve the detection of impedance anomalies linked with zones of elevated moisture, locally close to saturation, which can have a strong impact on the landslide activity. Finally, implementing more advanced seismic interferometry analyses, for instance including wavelet transforms, could be more helpful to investigate the frequency bands more subject to changes in seismic velocities throughout the slope. Data from the YJ network will also be useful to compare and contrast seismic measurements made by a distributed acoustic sensing (DAS) system that was deployed at the site broadly across the same time period (Ouellet et al., 2024; Watlet et al., 2024). A recommendation for future deployments of this nature would be to explore the use of large-n nodal systems that would be able to provide much higher spatial resolution and with lower deployment effort, although the suitability of such as deployment for long-term monitoring would be less favourable.

## Acknowledgements

The seismometers deployed in this report were provided via the NERC GEF (Loan 1127). We would like to thank all of the staff at SEIS-UK for their invaluable training and assistance with deployment issues and instrument repairs. Our thanks go to the staff in the BGS workshop who were able to help with the customisation of the deployment infrastructure. We would also like to thank Frances and James Standon for their continued support in permitting the HHLO to be operated on their land.

## Data and code availability

Data are archived on the SEIS-UK Octomore data management system and IRIS data management centre with network code YJ 2020 - 2023 (Watlet et al., 2020a). We used Obspy (Krischer et al., 2015 ; https://obspy.org) for computing the STA/LTA filters and

PPSDs, MSNoise 2.0 (Lecocq et al., 2014 ; https://www.msnoise.org) for computing the temporal HVSR, as well as the *dv/v* analysis, and SeismoRMS (Lecocq et al., 2020) for computing the ambient noise matrix plot. Visualisations have been made using Matplotlib (Hunter, 2007 ; https://matplotlib.org).

## Competing interests

List any competing interests, financial or otherwise, pertaining to any of the authors. If there are none, state that the authors have no competing interests.

## References

Bensen, G. D., Ritzwoller, M. H., Barmin, M. P., Levshin, A. L., Lin, F., Moschetti, M. P., Shapiro, N. M. & Yang, Y. 2007. Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. *Geophysical Journal International,* 169**,** 1239-1260.10.1111/j.1365-246X.2007.03374.x

Bièvre, G., Franz, M., Larose, E., Carrière, S., Jongmans, D., & Jaboyedoff, M. 2018. Influence of environmental parameters on the seismic velocity changes in a clayey mudflow (Pont-Bourquin Landslide, Switzerland). *Engineering Geology*, *245*, 248-257.

Boyd, J., Chambers, J., Wilkinson, P., Peppa, M., Watlet, A., Kirkham, M., Jones, L., Swift, R., Meldrum, P., Uhlemann, S. & Binley, A. 2021. A linked geomorphological and geophysical modelling methodology applied to an active landslide. *Landslides*.10.1007/s10346-021-01666-w

Boyd, J. P., Binley, A., Wilkinson, P., Holmes, J., Bruce, E. & Chambers, J. 2024. Practical considerations for using petrophysics and geoelectrical methods on clay rich landslides. *Engineering Geology*, 334, 107506.https://doi.org/10.1016/j.enggeo.2024.107506

Brisbourne, A. 2012. How to store and share geophysical data. Astronomy & Geophysics, 53, 4.19-4.20.10.1111/j.1468-4004.2012.53419.x

Chambers, J. E., Wilkinson, P. B., Kuras, O., Ford, J. R., Gunn, D. A., Meldrum, P. I., Pennington, C. V. L., Weller, A. L., Hobbs, P. R. N. & Ogilvy, R. D. 2011. Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK. *Geomorphology*, 125, 472-484.10.1016/j.geomorph.2010.09.017

Chambers, J., Holmes, J., Whiteley, J., Boyd, J., Meldrum, P., Wilkinson, P., Kuras, O., Swift, R., Harrison, H., Glendinning, S., Stirling, R., Huntley, D., Slater, N. & Donohue, S. 2022. Long-term geoelectrical monitoring of landslides in natural and engineered slopes. *The Leading Edge*, 41, 768-776.10.1190/tle41110768.1

Clarke, D., Zaccarelli, L., Shapiro, N. M. & Brenguier, F. 2011. Assessment of resolution and accuracy of the moving window cross spectral technique for monitoring crustal temporal variations using ambient seismic noise. *Geophysical Journal International*, 186**,** 867-882.https://doi.org/10.1111/j.1365-246X.2011.05074.x

Fiolleau, S., Jongmans, D., Bièvre, G., Chambon, G., Baillet, L., & Vial, B. 2020. Seismic characterization of a clay-block rupture in Harmalière landslide, French Western Alps. *Geophysical Journal International*, *221*(3), 1777-1788.

Guo, Z., Zhou, M., Huang, Y., Pu, J., Zhou, S., Fu, B. and Aydin, A., 2023. Monitoring performance of slopes via ambient seismic noise recordings: Case study in a colluvium deposit. *Engineering Geology*, *324*, p.107268.

Hobbs, P. R. N., Entwisle, D. C., Northmore, K. J., Sumbler, M. G., Jones, L. D., Kemp, S., Self, S., Barron, M. & Meakin, J. L. 2012. Engineering geology of british rocks and soils : Lias group. *In:* Northmore, K. J. (ed.).

Hunter, J.D., 2007. Matplotlib: A 2D graphics environment. *Computing in science & engineering*, *9*(03), pp.90-95.

Intrieri, E., Gigli, G., Mugnai, F., Fanti, R. & Casagli, N. 2012. Design and implementation of a landslide early warning system. *Engineering Geology*, 147, 124-136.https://doi.org/10.1016/j.enggeo.2012.07.017

Kelevitz, K., Novellino, A., Watlet, A., Boyd, J., Whiteley, J., Chambers, J., Jordan, C., Wright, T., Hooper, A. & Biggs, J. 2022. Ground and Satellite-Based Methods of Measuring Deformation at a UK Landslide Observatory: Comparison and Integration. *Remote Sensing*, 14, 2836

Krischer, L., Megies, T., Barsch, R., Beyreuther, M., Lecocq, T., Caudron, C. and Wassermann, J., 2015. ObsPy: A bridge for seismology into the scientific Python ecosystem. *Computational Science & Discovery*, *8*(1), p.014003.

Lane, V., Daly, D. & Hawthorn, D. 2020. SEIS-UK 6TD & ESPCD Field Methods Version 6.5. SEIS-UK, NERC. Latest version available at: https://seis-uk.le.ac.uk/equipment/downloads/6td_esp_manuals.php

Le Breton, M., Bontemps, N., Guillemot, A., Baillet, L., & Larose, É. 2021. Landslide monitoring using seismic ambient noise correlation: challenges and applications. *Earth-Science Reviews*, *216*, 103518.

Lecocq, T., Caudron, C. & Brenguier, F. 2014. Msnoise, a python package for monitoring seismic velocity changes using ambient seismic noise. *Seismological Research Letters,* 85**,** 715-726.10.1785/0220130073

Lecocq, T., Massin, F., Satriano, C., Vanstone, M. and Megies, T., 2020. SeismoRMS–A simple python/jupyter notebook package for studying seismic noise changes (Version 1.0), Zenodo. https://doi.org/10.5281/zenodo.3820046

Mainsant, G., Larose, E., Brönnimann, C., Jongmans, D., Michoud, C., & Jaboyedoff, M. 2012. Ambient seismic noise monitoring of a clay landslide: Toward failure prediction. *Journal of Geophysical Research: Earth Surface*, *117*(F1).

Merritt, A. J., Chambers, J. E., Murphy, W., Wilkinson, P. B., West, L. J., Gunn, D. A., Meldrum, P. I., Kirkham, M. & Dixon, N. 2013. 3D ground model development for an active landslide in Lias mudrocks using geophysical, remote sensing and geotechnical methods. *Landslides*, 11, 537-550.10.1007/s10346-013-0409-1

Nakamura, Y. 1989. Method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Report of RTRI (Railway Technical Research Institute) (Japan),* 30**,** 25-33

Oakley, D. O. S., Forsythe, B., Gu, X., Nyblade, A. A. & Brantley, S. L. 2021. Seismic ambient noise analyses reveal changing temperature and water signals to 10s of meters depth in the critical zone. *Journal of Geophysical Research: Earth Surface,* 126**,** e2020JF005823. https://doi.org/10.1029/2020JF005823

Ouellet, S., Dettmer, J., Lato, M., Cole, S., Hutchinson, D., Karrenbach, M., Dashwood, B., Chambers, J., Crickmore, R. 2024. Previously hidden landslide processes revealed using distributed acoustic sensing with nanostrain-rate sensitivity, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-3894692/v1]

Peppa, M. V., Mills, J. P., Moore, P., Miller, P. E. & Chambers, J. E. 2019. Automated co-registration and calibration in SfM photogrammetry for landslide change detection. *Earth Surface Processes and Landforms*, 44, 287-303.10.1002/esp.4502

Peterson, J. 1993. *Observations and modeling of seismic background noise*, US Geological Survey Reston, VA, USA.

Reis, W., Lindsey, J., Hill, P., Watkiss, N., Cilia, M., 2021. Omnidirectional Seismometers for Monitoring Slope Failure. NS25C-0438. AGU Fall Meeting 2021. New Orleans, USA.

Tonnellier, A., Helmstetter, A., Malet, J. P., Schmittbuhl, J., Corsini, A., & Joswig, M. 2013. Seismic monitoring of soft-rock landslides: the Super-Sauze and Valoria case studies. *Geophysical Journal International*, *193*(3), 1515-1536.

Uhlemann, S., Smith, A., Chambers, J., Dixon, N., Dijkstra, T., Haslam, E., Meldrum, P., Merritt, A., Gunn, D. & Mackay, J. 2016. Assessment of ground-based monitoring techniques applied to landslide investigations. *Geomorphology*, 253, 438-451.10.1016/j.geomorph.2015.10.027

Uhlemann, S., Chambers, J., Wilkinson, P., Maurer, H., Merritt, A., Meldrum, P., Kuras, O., Gunn, D., Smith, A. & Dijkstra, T. 2017. Four-dimensional imaging of moisture dynamics during landslide reactivation. *Journal of Geophysical Research: Earth Surface*, 122, 398-418.10.1002/2016JF003983

van Ginkel, J., Walter, F., Lindner, F., Hallo, M., Huss, M. and Fäh, D., 2024. Spectral characteristics of seismic ambient vibrations reveal subglacial hydraulic changes beneath Glacier de la Plaine Morte, Switzerland. *EGUsphere*, *2024*, pp.1-30.

Walter, M., Arnhardt, C., & Joswig, M. 2012. Seismic monitoring of rockfalls, slide quakes, and fissure development at the Super-Sauze mudslide, French Alps. *Engineering Geology*, *128*, 12-22.

Wathelet, M., Chatelain, J. L., Cornou, C., Giulio, G. D., Guillier, B., Ohrnberger, M. & Savvaidis, A. 2020. Geopsy: A user-friendly open-source tool set for ambient vibration processing. *Seismological Research Letters*, 91**,** 1878-1889.10.1785/0220190360

Watlet, A., Whiteley, J. & Chambers, J. 2020a. Yorkshire landslide observatory. International Federation of Digital Seismograph Networks, https://doi.org/10.7914/SN/YJ_2020

Watlet, A., Whiteley, J., Lane, V., Dashwood, B., Morgan, D., Chambers, J. E. & Lecocq, T. 2020b. Deployment of a long-term seismic network on a moisture-induced, slow moving, clay-rich landslide. S021-0014. AGU Fall Meeting 2020. San Francisco, USA.

Watlet, A., Wilkinson, P., Whiteley, J., White, A., Uhlemann, S., Swift, R., Ouellet, S., Chris, M., Meldrum, P., Jones, L. and Gunn, D., 2024. High-resolution geophysical monitoring of moisture accumulation preceding slope movement–a path to improved early warning. EarthArXiv. 10.31223/X5PM63

Whiteley, J., Uhlemann, S., Chambers, J. & Kendall, M. 2018. Seismic monitoring at the Hollin Hill Landslide Observatory. EGU2018-10275. EGU General Assembly Conference Abstracts. Vienna, Austria.

Whiteley, J. S., Chambers, J. E., Uhlemann, S., Wilkinson, P. B. & Kendall, J. M. 2019. Geophysical monitoring of moisture-induced landslides: A review. *Reviews of Geophysics*, 57**,** 106-145.10.1029/2018rg000603

Whiteley, J. S., Chambers, J. E., Uhlemann, S., Boyd, J., Cimpoiasu, M. O., Holmes, J. L., Inauen, C. M., Watlet, A., Hawley-Sibbett, L. R., Sujitapan, C., Swift, R. T. & Kendall, J. M. 2020. Landslide monitoring using seismic refraction tomography – the importance of incorporating topographic variations. *Engineering Geology*, 268**,** 105525.https://doi.org/10.1016/j.enggeo.2020.105525

Whiteley, J. S., Watlet, A., Kendall, J. M. & Chambers, J. E. 2021. Brief communication: The role of geophysical imaging in local landslide early warning systems. *Nat. Hazards Earth Syst. Sci.*, 21, 3863-3871.10.5194/nhess-21-3863-2021

Wilkinson, P., Chambers, J., Uhlemann, S., Meldrum, P., Smith, A., Dixon, N. & Loke, M. H. 2016. Reconstruction of landslide movements by inversion of 4-D electrical resistivity tomography monitoring data. *Geophysical Research Letters*, 43, 1166-1174.10.1002/2015gl067494

# Responses to review of “Seismic response of a slow-moving landslide: exploring data from two years of seismic monitoring at the Hollin Hill Landslide Observatory (UK)

## Reviewer 1

The manuscript presents a comprehensive study on the seismic monitoring of a slow-moving landslide at the Hollin Hill Landslide Observatory. The authors have made a significant effort in deploying a seismic network, collecting and analyzing data, and drawing preliminary conclusions. Overall, the paper has the potential to contribute valuable knowledge to the field of landslide research, but it also requires some improvements before publication.

We wish to thank Reviewer #1 for their numerous precious and valuable comments, which overall underscore the potential of this dataset to contribute to landslide research. However, we are unable to address all of these suggestions within the scope of this “data based report”, and therefore see this manuscript as a compromise between presenting an original dataset and showcasing its potential for conducting future cutting-edge landslide research. Therefore, we have tried to integrate as many suggestions as possible, but have chosen to restrict some further analyses, which require too many methodological developments and should be seen as follow-up original studies of their own. In order to clarify that our analyses are meant to pave the way for future, more in-depth work, we have expanded the discussion to include detailed perspective for future work (summarised in table 2).

Below, we respond to each individual comment, highlighting substantial changes brought to the manuscript.

Here are my detailed comments:

- A more in-depth discussion of the limitations of existing methods and how the proposed seismic monitoring approach aims to overcome them would enhance the introduction. For example, the authors could elaborate on the specific challenges in interpreting geophysical signals and models related to landslide processes.

Good suggestion. The introduction now includes two additional paragraphs clarifying the limitation of existing methods and specific challenges.

- The connection between the broader context of landslide hazards and the specific study at Hollin Hill could be strengthened. It would be beneficial to provide more global statistics or examples of landslide impacts to emphasize the significance of the research.

The introduction now includes a more detailed description of slow-moving landslides and their implication with regards to risk management.

- It would be useful to include more information about the spatial extent of the landslide and the distribution of different geological units across the site. This could help readers better understand the variability in the subsurface conditions and its potential impact on the seismic monitoring results.

This is now clarified in more details in section 1.2.

- The discussion of previous research at the HHLO could be organized more clearly. For example, presenting the key findings from geoelectrical monitoring and other studies in a tabular format could make it easier for readers to follow the evolution of research at the site and the relationships between different monitoring methods.

We understand your point but respectfully believe that presenting the evolution of the work at the HHLO in more detail is beyond the scope of this data-based report. Instead, since this has already been summarised in recent papers, we are pointing the readers towards relevant references where more details can be found.

- The description of the YJ network deployment is clear, but it would be beneficial to provide more information about the selection criteria for the specific sensor locations. Were there any pre-existing data or models that guided the placement? How were the "undisturbed," "dormant," and "active" areas defined, and what was the expected impact of these different zones on the seismic data?

Indeed, the sensor locations were determined according to pre-existing knowledge about the landslide structure. The landslide domains which Table 1 refers to have been identified by previous studies considering varying displacement rates across the slope (Boyd et al., 2021), areas of different hydrogeological conditions (Uhlemann et al., 2016b; Uhlemann et al., 2017) which allows us to test the hypothesis that seismometer setting will have an influence on the single-station analysis of seismological data. This is now clarified in the text.

- The discussion of sensor failures and data coverage is important. It would be helpful to include more details about the attempts to diagnose and address the issues with the failed sensors. Additionally, a more comprehensive analysis of the potential impact of the reduced data coverage from the failed sensors on the overall results and conclusions could be provided. For example, could the missing data from certain stations introduce biases in the event analysis or the interpretation of spatial patterns in the seismic response?

This is a valuable comment and we agree that the reduced data coverage in the second year (with only >70% data coverage) impacts some data investigation. However, the impact on the data investigation is expected to be relatively minimal since at least one seasonal cycle has been captured at >95% data coverage, and at least one sensor in each landslide domain remained active throughout the monitoring period. We have now added a few more words mentioning this in Section 2 and also added this element in the limitations outlined in Section 4.5.

- The discussion of noise sources could be expanded. In addition to the identified farming and highway noise, it would be interesting to explore whether there are any other potential sources of noise, such as nearby industrial activities or natural sources like wind. A more detailed analysis of the noise characteristics in different frequency bands and how they vary over time could also provide valuable insights. For example, are there any diurnal or seasonal patterns in the noise levels that could affect the interpretation of the seismic data?

We have included more information on the potential sources of noise, including wind and sheep presence in the field in Section 3.2. We believe that the spectrograms presented in Figure 5 already offer a solid base for describing noise characteristics of the YJ network. Figure 5a displays a general overview of the noise levels in the 0.05 - 100 Hz, from which the seasonality in the low-frequency noise (0.1 - 0.5 Hz) can be observed, which relates to higher intensity in microseism in winter due to the increased occurrence of storms in the UK. Then Figure 5b displays the higher frequency noise attributed to anthropogenic and farming sources.

- The application of STA/LTA filters and the detection of seismic events are well-described. The identification of a signal potentially related to landslide activity is interesting. However, more evidence could be provided to support this claim. For example, could the authors perform a more detailed spectral analysis of the signal to further characterize its frequency content and compare it with known seismic signatures of landslide processes? Additionally, it would be useful to investigate whether the occurrence of this signal correlates with other observable changes at the landslide, such as changes in slope displacement or soil moisture.

Providing additional evidence to support the hypothesis that the highlighted event type is related to landslide activity would indeed strengthen the manuscript. We note that these events are recorded across the network at several occasions (>100 times), but are primarily picked by stations YJ.2002 and YJ.2004, both in terms of arrival time and energy, suggesting a landslide-related origin. These two stations are indeed located in the most active part of the landslide, and closer to the disturbed clay material. The harmonic pattern seems consistent with expectations of seismic signals generated by crack openings, as demonstrated for instance by Chouet (1986) or Sickin and Malin (2019). Such short-duration (<2s) events have also been recorded in a similar landslide context, at the Super-Sauze landslide, by Vouillamoz et al. (2018).

We are aware that classic STA/LTA filters are limited in terms of detecting very low energy events, and we believe that they might not be efficient in detecting precursors of slope movement generated by ductile wetted clay material. We formulate the hypothesis that the present event type can be attributed to crack opening during clay shrinkage, as supported by analogue in the litterature. In clay-rich slopes, there has been discussion regarding the potential for clay shrinkage to act as a preconditioning factor for subsequent landslide movement. Increased opening of cracks under dry conditions may promote water infiltration rather than runoff during subsequent rewetting periods, potentially explaining localized zones of elevated moisture that could drive slope failure. Techniques capable of detecting crack openings during the drying process could therefore help identify areas of interest where slope movement is more likely during later wet periods. We therefore consider these events to be relevant for landslide monitoring and suggest that they could be further investigated in future studies.

While a more detailed spectral or source-mechanism analysis could indeed provide additional insights, we believe that such analyses are beyond the scope of the current data-based report. Moreover, a recent study by Murray et al. (2025), has addressed the seismic event detection at the HHLO site using the single station AU07 from the UKArray network (which was not included in the analyses we present in this work). In their study they applied a machine-learning detection approach to the HHLO site and provided a thorough characterization of landslide-related seismicity, including spectral properties. We have therefore decided not to make further analyses in this revised section of the manuscript. We have rather added discussion elements strengthening the interpretation of the displayed event type, and then we rely on Murray et al. (2025) to illustrate the potential of the YJ network data for applying a similar machine-learning analysis and investigating spatial patterns related to landslide activity. The paper by Murray et al. (2025) is a good example of the type of more detailed investigation that we hope other researchers may take on through the description of the YJ network in this data-based report.

- The analysis of tilt data and its relationship with soil moisture and matric potential is a valuable contribution. The figures effectively illustrate the trends in tilt and the comparison with other parameters. However, it would be beneficial to discuss the possible mechanisms underlying the observed relationship in more detail. For example, how does desiccation cracking exactly affect the sensor tilt, and what are the implications for the interpretation of slope deformation? Are there any other factors that could potentially influence the tilt measurements, and how were they accounted for?

Following comments from Reviewer#2, we have considerably re-worked the tilt section. It now features tilt in degrees, as derived from the seismic traces following the approach developed by Wenner et al. (2022), which use a very low pass filter to extract tilt below the corner frequency, and then use the instrument response to convert the counts in degrees of tilt (see my detailed answer to Reviewer#2 for more information). About the mechanisms driving the trends in tilt at the seasonal scale, we have now included some reflections in the updated tilt section. We believe that tilt induced by clay shrink–swell is likely linked to volume changes in the disturbed upper clay layer (~2 m), where desiccation cracking may generate local rotational deformation depending on the morphology of the upper layer most affected by volume change. For instance, zones close to compression ridges are expected to accommodate volume change differently than the flow lobes areas. Repeated LiDAR scans of the slope have already highlighted seasonal uplift of several tens of centimetres during the wet months (Watlet et al., 2024) at the HHLO. Kelevitz et al. (2022) investigated slope deformation at the HHLO via long-term InSAR analyses and found that seasonal displacement was strongly correlated with volumetric water content. They suggest that these vertical changes are driven by volumetric deformation linked to the wetting and drying of the mudstone. Observations in these two studies tend to confirm slope-scale shrink-swell processes, and support the seasonality observed in our seismically-derived tilt timeseries.

Comparison of tilt signals recorded during an attested slope movement has also now been included in the section, to highlight the potential of seismically-derived tilt data to inform on actual slope movement (see new Figure 8).

We now also include a word on other factors affecting tilt, and particularly sensor levelling issues that could bias the retrieved tilt data. Such problems are not expected to result in tilt signals correlated with matric potential, but are likely to add additional drift to the data. This is in fact visible for one of the seismometer, YJ.2001, for which mass positions rapidly went out-of-range in the first months of the deployment. This resulted in a strong polynomial trend, which prevented retrieval of meaningful tilt data. This is now reflected in the new Figure S1.

- The approach for computing the H/V ratio and the analysis of temporal spectrograms are clear. The identification of seasonal variations in secondary peaks and their relationship with perched water tables and impedance contrast is interesting. However, further interpretation of these findings in the context of the overall landslide behavior could be provided. For example, how do these changes in the H/V ratio relate to the stability of the landslide? Could the authors use the H/V ratio data to infer any changes in the subsurface structure or material properties?

We have reworked the H/V section in the revised version of the manuscript. Former figures 8 and 9 have been combined (now Figure 9), while expanding the number of displayed stations to strengthen the results description (in a response to comments by reviewer #2). We have also expanded the discussion of the findings. The H/V ratio changes seem more correlated to change in pore water pressure, which is known to be linked to crucial slope stability parameters like Poisson’s ratio. Using H/V ratios to derive changes in Vs and then shear modulus would be an interesting follow up research topic. We have added a few words on this in Section 4.5 and in table 2 summarising the perspective for future work based on the YJ network dataset.

- The ambient noise cross-correlation analysis is promising, but the results could be presented in more detail. The link between soil moisture and velocity change is demonstrated, but a more quantitative analysis of the relationship would be beneficial.

Providing a more quantitative analysis would indeed be beneficial, but we believe this goes beyond the scope of this data-based report. Instead, we have included this follow-up research question in table 2.

- The discussion section effectively summarizes the main findings and their implications. The recognition of the challenges related to sensor tilting, noise, and source location analyses is important. However, the proposed solutions, such as deploying more robust sensors, could be further explored. What are the specific advantages and disadvantages of different types of seismic sensors in this context, and how would they address the identified issues? Additionally, a more comprehensive discussion of the potential limitations of the current study and how they could impact the generalizability of the results would be valuable.

We have included a list of immediate limitations surrounding the analysis undertaken in this study, relating to i) lack of noise analysis, ii) impact of failed sensors, iii) tilt, iv) etc. Furthermore, we have suggested areas of further research in Table 2.

Overall, the manuscript requires some revisions to improve the clarity and depth of the presentation. The authors should address the specific comments provided above to enhance the scientific rigor and value of the study.

**Reviewer 2**

This paper as I interpret it has two main points: 1) to present and share the seismic datasets generated at the HHLO (hence it's later description in the Conclusion as a Data-based report), and 2) to describe some first interpretations of those data as a means to share observations and motivate future study. As a data report presenting the monitoring network and dataset I think this paper generally succeeds, although it needs to be more upfront with that aspect in the title and abstract to give readers a clear expectation on the purpose of the paper. As a report analyzing preliminary interpretations I think this paper needs more development. For example, the attribution of a certain harmonic signal to crack opening seems plausible but there is no accompanying data/observation/reference/model to support that interpretation so it comes off as purely speculative and unsupported. Meanwhile, sensor tilt is not described in the text until we arrive at that section, it's never mentioned how tilt is calculated and the results shown in 10^6 counts, and probably more could be learned by understanding tilt orientations for stations in the unstable/cracked area of the slope. And it has to be said both these observations as described really only relate to desiccation cracking, not strictly landslide processes. Generally I found the other interpretations similarly lacking of substantiation and detail, and suggest that this aspect of the paper needs further development. I'd really like to see the interpretations presented less as technique by technique and more centered around particular landslide phenomena. I have attached an annotated PDF that includes these and other comments.

We are thankful to reviewer #2 for their in-depth review comments and suggestions which greatly improve this manuscript. We are glad to see that our manuscript is deemed successful at its primary Seismica's data-based report manuscript typeobjective, i.e. presenting the dataset as a data-based report. We also acknowledge that more developments are needed to make it an original research paper analysing preliminary results. Finding the right compromise between highlighting promising research outputs and providing sufficiently detailed analyses is a difficult exercise, and certainly comes with frustrations, including for the authors themselves. Since we want to take advantage of Seismica’s *data-based report* manuscript type in providing a means to promote openly available seismic datasets, we believe that we should keep the analyses limited and somewhat illustrative, rather than producing a lengthy paper trying to achieve too many objectives. In line with our response to reviewer #1, while we have tried to incorporate as many suggestions as possible by adding substantial new analyses to the previous version of the manuscript, we have also chosen to orient this manuscript as a report presenting the dataset and teasing its potential for landslide research by highlighting 4 main areas of research that can be investigated in follow-up works.

We have integrated the vast majority of your suggestions from the annotated PDF, and have extracted the main comments in the list below, which also includes our individual responses.

- Title: This title is nice but I don't think it fits the scope of the paper, which is in fact a "data-based report" article type. It's not until the conclusion that this particular scope is clearly mentioned, and the motivating goal to present and share the data generated. So how to revise? One suggestion might be to add specifying language following this title after a colon., like ": datasets and preliminary interpretations"

We agree that the title needs to be modified in order to clarify the main scope of the manuscript. Following your suggestions, we now call it: *Seismic response of a slow-moving landslide: exploring data from two years of seismic monitoring at the Hollin Hill Landslide Observatory (UK)*

- Abstract: Here I suggest you conclude with a statement of the purpose and scope of the paper being also to share the data generated, and toward what broader goal.

We have added a concluding sentence clarifying the main scope of the paper.

- Line 121: usually this paragraph states very briefly what you found and what you hope might come from this study. not sure you need to end this with another motivation sentence, which rather might belong in the above paragraphs

Agreed, this is now moved to the previous paragraph.

- Figure 1: with the color overlay on this image I can't really see any of the landslide features. I generally also appreciate more photos in such a figure, if possible

Figure 1 has been completely re-designed and now includes hillshade topography better highlighting landslide features and improving visibility of the color overlay. Photos of the main landslide features have also been included.

- Line 175: what is this hanging paragraph about? does it belong with the prev? It doesn't seem to have a particular topic of its own or if it's key it needs some elaboration

You are right that this paragraph doesn’t really bring any useful information, hence we removed it and replaced it by a short paragraph presenting a very recent microseismic study focusing on a long-term dataset of a single seismic station deployed at Hollin Hill as part of a regional seismic network.

- Line 226: This is a detail that will not age well in the main body of a manuscript text, rather should be part of the data availability statement

Agreed, especially that now the embargo is lifted. Now placed in the data availability statement.

- Line 230: this is stated by not justified, and the point of the secondary microseism comes rather out of the blue (hope all the readers know what that is!). i don't think that the observation of the secondary microseism generally supports the statement of data quality for the network, that would seem to me to need further justification.

Good point, the noise analysis has been expanded and now clarifies the secondary microseism aspect.

- Figure 4: I suggest this figure be revised for clarity: a) don't both to show data for >30 sec, on this or the other panel, and b) adjust the c-axis scale which is currently being thrown off by high concentrations in the useless period area making it so you can't see details in the actual frequency range of interest

The figure has been modified to incorporate your suggestions.

- Line 240: I see lots of high frequency noise periods on Figure 5, when is the breeding season? Maybe this needs noted or stated.

There isn’t a clear breeding season, but the sheep are rather breeding in the field on a sporadic basis, each time for a few weeks. This is now clarified in the text.

- Figure 5: c-axis looks to be mislabelled as H/V when what appears to be shown here is spectral power or amplitude

Well spotted, now replaced to Amplitude [dB].

- Line 255: interesting, and I don't disagree, but I think you need to include some further discussion and references that back up this interpretation. also: what do the particular harmonic frequencies seen so clearly in the spectrogram relate to, and why are there two main frequencies excited by these event types??

The harmonic frequencies generated by this type of event remain difficult to explain without more detailed source analyses, which lie beyond the scope of this data-based report. However, similar seconds-long, narrow-band signals have been reported during brittle failure and crack opening in landslide contexts, as well as in analogous environments. Vouillamoz et al. (2018) reported short-duration (< 2 s) quake-like signals associated with landslide activity (termed *slidequakes*). While they only observed harmonic components in longer events at the Super-Sauze landslide, other studies have highlighted the potential for finite fractures to resonate or oscillate during rapid opening. Sicking and Malin (2019) showed that fracture openings can generate short-duration energy pulses and harmonic resonances of the entire fracture, and Chouet (1986) discussed the resonant modes of cracks, demonstrating that modeled cracks produce multiple discrete frequency peaks whose frequencies depend on crack length and boundary stiffness. Such modeling experiments seem transferable to our landslide context and could explain the harmonic frequencies of our particular event. A more detailed spectral and source-mechanism analysis would be required to confirm this interpretation.

Furthermore, the fact that mainly brittle deformation generates energy high enough to be detectable with conventional STA/LTA approaches seems plausible. More ductile movements in highly wetted clay materials are likely to be less efficient at radiating seismic energy. More advanced, machine-learning algorithms are likely to help detecting smaller local events potentially associated with landslide activity. Recently, a machine-learning event-detection approach was successfully trialled at the HHLO site by Murray et al. (2025), based on the single-station AU07 broadband sensor from the UKArray network installed at the site. In this study, they detected a significant number of events preceding landslide movement, promoting promising expectations for a similar approach to be applied in the future to the YJ network, thereby providing improved spatial information.

Since Murray et al. (2025) is directly relevant to, (and more advanced than) the event analysis included in this manuscript, we decided to keep the original analysis and refer to their study to illustrate the potential of the YJ network dataset with respect to seismic activity induced by the landslide activity. In addition, section 4.1 now includes the discussion elements mentioned earlier in this response as a complementary discussion on the potential mechanisms explaining the harmonic frequencies of the displayed event type.

References:
Chouet, B., 1986. Dynamics of a fluid-driven crack in three dimensions by the finite difference method. Journal of Geophysical Research: Solid Earth, 91(B14), pp.13967-13992.
Murray, D., Stankovic, L., Stankovic, V., Pytharouli, S., White, A., Dashwood, B. and Chambers, J., 2025. Characterisation of precursory seismic activity towards early warning of landslides via semi-supervised learning. Scientific Reports, 15(1), p.1026.
Sicking, C. and Malin, P., 2019. Fracture seismic: Mapping subsurface connectivity. Geosciences, 9(12), p.508.
Vouillamoz, N., Rothmund, S. and Joswig, M., 2018. Characterizing the complexity of microseismic signals at slow-moving clay-rich debris slides: the Super-Sauze (southeastern France) and Pechgraben (Upper Austria) case studies. *Earth Surface Dynamics*, *6*(2), pp.525-550.

- Line 259: How is this being determined?? The plots show tilt in counts, what does that mean? Without knowing how it's computed I'm skeptical of what it represents. This aspect comes really out of the blue for me as a reader.

One important aspect of landslide monitoring is to track ground movement on or before (preferentially before) they occur. Conventional tiltmeters are used to inform on surface tilt induced by rotational movement in a landslide. The general idea of this section of the manuscript is to assess whether seismic traces can also be used to inform on subsurface tilt generated by slope deformation.

The original plots in the previous version of the manuscript were displaying the outputs of the mass positions recorded by the Taurus datalogger. Since these data are indeed difficult to interpret in counts and aren’t available on the EarthScope repository, we have decided to focus on extracting the tilt data from the seismic traces instead. This has been achieved following the approach detailed in Wenner et al. (2022) which applies a low pass filter at very low frequency on the seismic trace in order to extract the tilt signal, and then using the instrument response to convert the counts into tilt angles. In their paper, they mainly focus on tilt data for short periods of time, and do not analyse seasonal tilt. For the very low-frequency data (periods below the instrument's lower corner frequency), this conversion requires integrating the digitizer output signal and subsequently scaling the resulting time series by a factor that includes the instrument's corner frequency, sensitivity, and the negative gravitational acceleration. In our case, we are interested in both the tilt for a short period of time (i.e. for slope movement following rainfall events), and seasonal tilt potentially linked to clay shrink-swell processes.

Since the mass position data highlighted strong variability continuously across the monitoring period, we wanted to first focus on retrieving the continuous tilt timeseries, which has been a bit more challenging than expected. In the tilt retrieval process from Wenner et al. (2022), detrending the data is required, and in most cases a simple linear trend is sufficient. However, some traces contain gaps. Detrending each segment separately has the chance to detrend meaningful tilt data. For each seismometer channel, our approach therefore consisted of fitting a general trend on the whole trace, adjusting the trace segments to correct the remaining steps, and then detrending the resulting trace to retrieve a tilt signal. This assumes no tilt change between the start and the end of the trace, and is therefore not able to highlight a long-term trend in tilt. In the context of seasonal tilt, it is therefore mainly valid in the presence of full seasonal cycles, but has the limitation to remove any long term linear trend in the tilt data, as visible in the new Figure S1.

Reference: Wenner, M., Allstadt, K., Thelen, W., Lockhart, A., Hirschberg, J., McArdell, B.W. and Walter, F., 2022. Seismometer records of ground tilt induced by debris flows. *Bulletin of the Seismological Society of America*, *112*(5), pp.2376-2395.

- Line 261: consider showing tilt magnitude and azimuth instead of raw channel data, i.e., make N/E records into a vector and analyze that instead, maybe the tilt directions relate to crack orientations? Also, some of the stations are on stable ground, these seem less interesting to me than tilts computed on unstable areas.

Showing tilt in terms of magnitude and azimuth is indeed a good idea. Having looked at it, it seems that the tilt azimuths do not highlight clear directions that could be related to crack orientations. We have therefore preferred rotating the tilt data to display them in terms of downslope and cross-slope directions, which also allows easier comparison with newly added tilt data from tiltmeters installed on the slope, and which are also providing tilt in downslope and cross-slope directions. In the new figure 7, we still display some of the tilt data from stable locations, to emphasize the difference with unstable locations.

- Figure 7: Need to label these stations as YJ.2001 etc, otherwise they look at first glace like years which is of course confusing. a) the color scheme here and in c) is confusing, so closely related but not the same datasets. b) how does 10^6 counts relate to tilt?! c) why show E-N and not mag/azimuth? d) what differences are there for stable/landslide stations?

Figure 7 has been completely redesigned following most of your suggestions (see responses to the two previous comments). We believe that it is now more insightful. The tilt has been converted in degree, rotated along slope direction, and displays more clearly the landslide domains (above, within and below movement zones).

- Line 288: wait though, what about the primary peak, why not analyze that and suggest what it relates to?

This section now includes a description of the primary peak and secondary peaks. Figure 8 and 9 have been combined to strengthen the analysis.

- Line 291: what data do you have / show to support these interpretations?

These interpretations rely on previous hydrological and geological studies performed at the site. This is now clarified in the text.

- Line 292: Not sure I agree with that comment! Or maybe I just don't know what you mean by it.

Now removed as it was not really justified.

- Line 294: where are shear wave velocity data shown to support this interpretation? if not there, you need to indicate this is your interpretation, or are 'likely linked’

Previous studies investigated shear wave velocity variations at the HHLO (Whiteley et al., 2021). This is now referenced in the text.

- Figure 10: a) Maybe it's my bias, but I don't see this subplot as necessary, I believe you! b) Suggest you look at temperature as well as there could be a thermo-elastic mechanism driving these dV results.
    a) We understand your point but have decided to keep it as a rather illustrative figure.
    b) Good suggestions. Having looked into this, the thermo-elastic mechanism driving the dV results remains an open question, as temperature and

moisture are generally correlated at the site. Strong shifts in dv/v occur both in winter and summer, which suggests a stronger correlation with wetting processes and rainfall. Nevertheless, we have added a word mentioning temperature as a potential origin in the manuscript.

- Line 343: I would for sure not describe nodal geophone arrays as more "robust" than your deployments!

Right, this has been rephrased.

- Line 347: Yes, but did we learn anything about landslide processes yet from these data? So far you describe ground moisture changes and possible desiccation cracking, but nothing about landslide processes.

Good point. In line with the modifications integrated in the introduction regarding the formation of fissures in dry conditions and the fact that slow-moving landslide experience a rather ductile behaviour, we modified to rather mention “subsurface processes”, which has a broader meaning. We also want to underscore that the opening line of the abstract speaks to “processes that drive slope destabilisation” rather than the processes of slope stabilisation themselves.

- Line 359: not really suitable to reference an in-prep publication, and it makes me wonder what is presented in that paper and how it relates to this one.

Citation modified as it has now been published.

# Seismic response of a slow-moving landslide: exploring data from two years of seismic monitoring at the Hollin Hill Landslide Observatory (UK)

A. Watlet[1^,2], J. Whiteley[1^,3], B. Dashwood[1], D. Morgan[1], V. Lane[4], L. Finch[4], D. Gunn[1*], T. Lecocq[5], J. Chambers[1*]

[1]Shallow Geohazards and Earth Observation, British Geological Survey, Nottingham, United Kingdom
[2]Environmental Sensing and Modelling, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg
[3]Ground Engineering & Tunnelling, AtkinsRéalis, Bristol, United Kingdom
[4]SEIS-UK, University of Leicester, Leicester, United Kingdom
[5]Seismology - Gravimetry, Royal Observatory of Belgium, Belgium, Brussels, Belgium
^Honorary Research Associate of the British Geological Survey
*Retired
[*]Corresponding author: arnw@bgs.ac.uk

## Author ORCIDs

A. Watlet: 0000-0003-0318-9032
J. Whiteley: 0000-0001-5254-4817
B. Dashwood: 0000-0002-8396-861X
V. Lane: 0000-0002-9156-114X
T. Lecocq: 0000-0002-4988-6477
J. Chambers: 0000-0002-8135-776X

## Author contributions

Conceptualization: A. Watlet, J. Whiteley
Data Curation: A. Watlet, J. Whiteley
Formal Analysis: A. Watlet
Funding Acquisition: J. Chambers, D. Gunn, T. Lecocq, A. Watlet, J. Whiteley
Investigation: B. Dashwood, D. Morgan, A. Watlet, J. Whiteley
Methodology: A. Watlet, J. Whiteley
Project Administration: V. Lane, A. Watlet, J. Whiteley
Resources: V. Lane, L. Finch
Software: A. Watlet, T. Lecocq
Supervision: J. Chambers
Visualization: A. Watlet
Writing – original draft: A. Watlet, J. Whiteley
Writing – review & editing: A. Watlet, J. Whiteley

The first two authors contributed equally to the production of this study.

## Abstract

Early-warning of landslide failure relies on understanding subsurface processes that drive slope destabilisation, including ~~typically~~ changes in moisture content or mechanical behaviour. Material heterogeneity in landslide systems causes spatiotemporal variation in these dynamic processes. There is therefore a need to develop methods that can detect and measure changes in the subsurface to inform landslide stability. Seismic monitoring can record information on the elastic behaviour of the ground in response to immediate and long-term processes, such as slope displacement and moisture variation ~~respectively~~. Here, we report on data acquired by a seismic network deployed at a slow-moving clay-rich landslide in North Yorkshire UK, representative of many landslides in clay-rich lowland slopes. The temporary network was operational for two years with the aim of understanding how the seismic response of the landslide varies between sensors deployed ~~to~~ on parts of the landslide with distinctly different hydrogeological properties. We present an overview of the rationale and deployment procedure, as well as a preliminary assessment of data quality, event analysis, tilt observations, * H/V ratio calculations, and ambient noise cross-correlation. We conclude that the moisture dynamics of the slope have a significant influence on observed data, and make further recommendations for the analysis of the dataset. Our study ~~The main purpose of this manuscript is to~~: ~~i)~~ demonstrates the feasibility of analytical techniques using these data, ~~ii)~~ promotes the unique dataset to foster further in-depth analysis, and ~~iii)~~ encourages similar seismological deployments on active landslides.

## Résume (French)

La détection précoce des glissements de terrain repose sur la compréhension des processus souterrains qui conduisent au déclenchement des évènements, généralement liés à des variations de teneur en eau ou de comportement mécanique. L’hétérogénéité structurelle des glissement de terrain peut entraîner une variabilité spatio-temporelle de ces processus dynamiques. Il est donc important de développer des méthodes permettant une meilleure observation de ces changement dans le sous-sol pour évaluer la stabilité des pentes. La surveillance sismique, par l’utilisation de capteurs déployés à la surface du glissement de terrain, peut permettre d’enregistrer des informations sur le comportement élastique du sol, en réponse à des phénomènes tels que les déplacements en surface et les variations d’humidité. Nous décrivons ici le jeu de données acquis par un réseau sismique déployé sur un glissement de terrain argileux à déplacement lent dans le North Yorkshire, au Royaume-Uni, représentatif d’un grand nombre de glissements de terrain argileux dans le monde. Le réseau temporaire, déployé sur une durée de 2 ans, avait pour but de comprendre comment la réponse sismique varie dans des zones du glissement de terrain aux propriétés hydrogéologiques différentes. Nous présentons un aperçu de la procédure de

* in abstract, might need defined first or spelled out
-> only defined line 406

déploiement, ainsi qu'une évaluation de la qualité des données, de l'analyse des évènements, des observations de tilt, des calculs de rapport H/V, et de la corrélation croisée du bruit ambiant. Les premières conclusions indiquent que les données observées sont significativement influencées par la dynamique de l'humidité du sol de la pente, et nous permettent de formuler des recommandations pour l'analyse du jeu de données. L'objectif principal de ce manuscrit est : i) de démontrer la faisabilité des techniques d'analyse appliquées à ces données ; ii) de promouvoir ce jeu de données pour encourager des analyses plus approfondies ; iii) et de favoriser la mise en place de déploiements sismologiques similaires sur des glissements de terrain actifs. évaluation de la qualité des données, des analyses d'événements, des observations de basculement, des calculs de rapport H/V et des corrélations de bruit ambiant.

## Non-technical summary

Early warning of landslides is important for safety, and often relies on rainfall thresholds or on assessing visible signs of surface deformation. It is usually how wet the subsurface of the landslide is that drives slope failure, and surface deformation generally occurs late in the process, thus with limited to no time for mitigation measures to be ~~efficiently~~ put in place. There is a need for innovative methods to observe and measure changes occurring underground. Seismic monitoring involves placing sensors measuring vibration on the landslide surface to track how the ground moves and responds over time, especially to changes in moisture. We set up a network of these sensors at a slow-moving landslide in North Yorkshire, UK. The goal was to see how the seismic readings differed in areas with different water content and ground properties. We explain why and how we set up the sensors, and present the data we collected. Our findings show that changes in moisture significantly affect how the ground responds, and how landslide activity can generate specific vibrations. Finally, we offer suggestions for further analyses.

## 1. Scientific background and motivation

### 1.1 Introduction

Landslide hazards impact population safety and infrastructure across the globe. The risk of landslides can be mitigated through engineering interventions or management, with the latter often favoured due to lower costs, particularly where slow-moving landslides are prevalent. One such method of landslide management is the implementation of an early-warning system that uses field observations to warn of impending slope failure events, thus allowing time for more efficient intervention planning or removal of the elements at risk (Intrieri et al., 2012). Slope-scale early warning systems typically tend to rely on observations of rainfall, ground moisture, or slope displacement to predict future failure events (Pecoraro et al., 2019).

Slow-moving landslides are ~~those~~ characterised by slow ground motion, spanning from millimeters to meters per year, often seasonally influenced and persisting for long periods of time, from years to decades (Lacroix et al., 2020). Such landslides typically occur in geological contexts involving clay-rich or mechanically weak materials, and in areas with strong seasonal rainfall patterns. Despite slow-moving landslides being perceived as low risk to human life, they can lead to significant damages to critical infrastructure (such as road and railway network) and can be difficult to manage effectively (Gibson et al., 2013).

In recent years, geophysical techniques have been increasingly used for slope monitoring (Whiteley et al., 2019). Geophysical techniques offer unique advantages in that they can often obtain measurements from across large areas of the subsurface (unlike point sensors) and are able to infer processes occurring at depth within a landslide body (unlike surface observations). However, the sensitivity of geophysical methods to proxies, rather than direct measurements, of subsurface ground conditions means there can be ambiguity in interpreting the spatial and temporal variation in geophysical signals and related models (Le Breton et al., 2021). Identifying precursors to landslide events with sufficient lead time is particularly ~~difficult.~~ challenging

* Geoelectrical monitoring has the advantage of providing detailed images of the subsurface at fixed time intervals, but its temporal resolution is limited due to the time required for data acquisition (typically >1 hour). Additionally, it is primarily sensitive to changes in the ground directly beneath the deployed sensor array; where electrodes are used outside of the zone of interest, changes in ground conditions are detectable but difficult to localise (Bièvre et al., 2021). In contrast, seismic monitoring using a network of seismometers provides time-continuous data and the ability to detect events both proximal and distal to the sensor array, offering insights into the mechanical properties of landslide materials, making it particularly valuable for detecting and monitoring dynamic slope processes (e.g., Feng et al., 2025). the approach

In clay-rich slopes, deformation typically occurs under saturated or near-saturated conditions, exhibiting elastoplastic rather than brittle and inelastic behaviour. This likely affects the level of microseismic activity expected from slope movement (Walter et al., 2013). However, changes in shear strength due to elevated moisture and the distribution of scatterers ?? caused by deformation likely impact seismic signals at the slope scale (Vouillamoz et al., 2018). Seismic monitoring could also shed new light on shallow processes affecting clay-rich slopes in drier conditions, such as the formation of desiccation cracks and fissures (Yfantis et al., 2021). The presence of fissures linking a permeable top layer and deeper slip surfaces are thought to play a role as a landslide triggering mechanism (Van Asch et al., 1999). Therefore, in addition to advancing our understanding of

* A topic sentence about geoelectric methods seems out of place, I would lead w/ seismic or better set up paragraph topic sentence

landslide processes during periods of increasing and full saturation, improving our ability to observe fissure generation in dry conditions might advance our understanding of landslide mechanisms.

Here, we present data and initial findings from a deployment of seismometers (the YJ 2020-2023 temporary network) at a slow-moving, clay-rich landslide in North Yorkshire, UK. The primary objective of this study is to encourage further, more advanced investigations on the acquired dataset, which has been made available for use by other researchers working in this field. Seismic monitoring ~~lies as~~ is a complementary technique to the systems already deployed at the site, which have largely focused on understanding soil moisture dynamics through geoelectrical monitoring and soil sensor deployment (Uhlemann et al., 2016a).

### *1.2 Site description*

The Hollin Hill Landslide Observatory (HHLO) is a field observatory and laboratory that has been operated by the British Geological Survey (BGS) since 2008. The site has been important in the research and development of novel geophysical, geotechnical and remote sensing technologies for the observation and monitoring of natural landslide processes. The Hollin Hill landslide is a slow-moving, clay-rich landslide, which is seasonally reactivated when soil moisture increases in winter (Uhlemann et al., 2017). In summer, it experiences high shrinkage and surface fissuring, which may consequently impact the hydrological regime of the landslide in following years. The HHLO is representative of many landslide hazards in clay-rich lowland slopes worldwide, with the underlying Lias Group rocks accounting for 15% of all landslides in the UK (Hobbs et al., 2012).

The HHLO is located on a south facing slope made of a series of interbedded, north-dipping, shallow marine mudstones and sandstone, comprising (in descending order): the Dogger Formation (DF), which is a limestone and sandstone unit acting as a minor aquifer, the Whitby Mudstone Formation (WMF), the Staithes Sandstone Formation (SSF), and the Redcar Mudstone Formation (RMF) (Chambers et al., 2011). The WMF is the main unit prone to failure. Most of the reported movement occurs on a grass field covering 5 ha of land. The top of the slope exhibits rotational failures in the WMF leading to the formation of prominent backscarps, the most recent of which has been developing since 2016 (Boyd et al. 2021). The landslide failure mode becomes translational mid-slope, with some large flow lobes of mudstone materials creeping on top of the SSF toward the base of the slope (Figure 1). ~~It is understood that~~ the cycle of slope movement initiates with the WMF reaching its liquid limit in the mid-slope, which then starts to move translationally. This removes support for the upslope, which initiates the formation of backscarps. Translationally failed WMF from the mid-slope progresses down slope until it is emplaced above the SSF, into which it drains and movement is arrested, leaving slowly progressing flow lobes toward the base of the hill.

Great update to this figure!

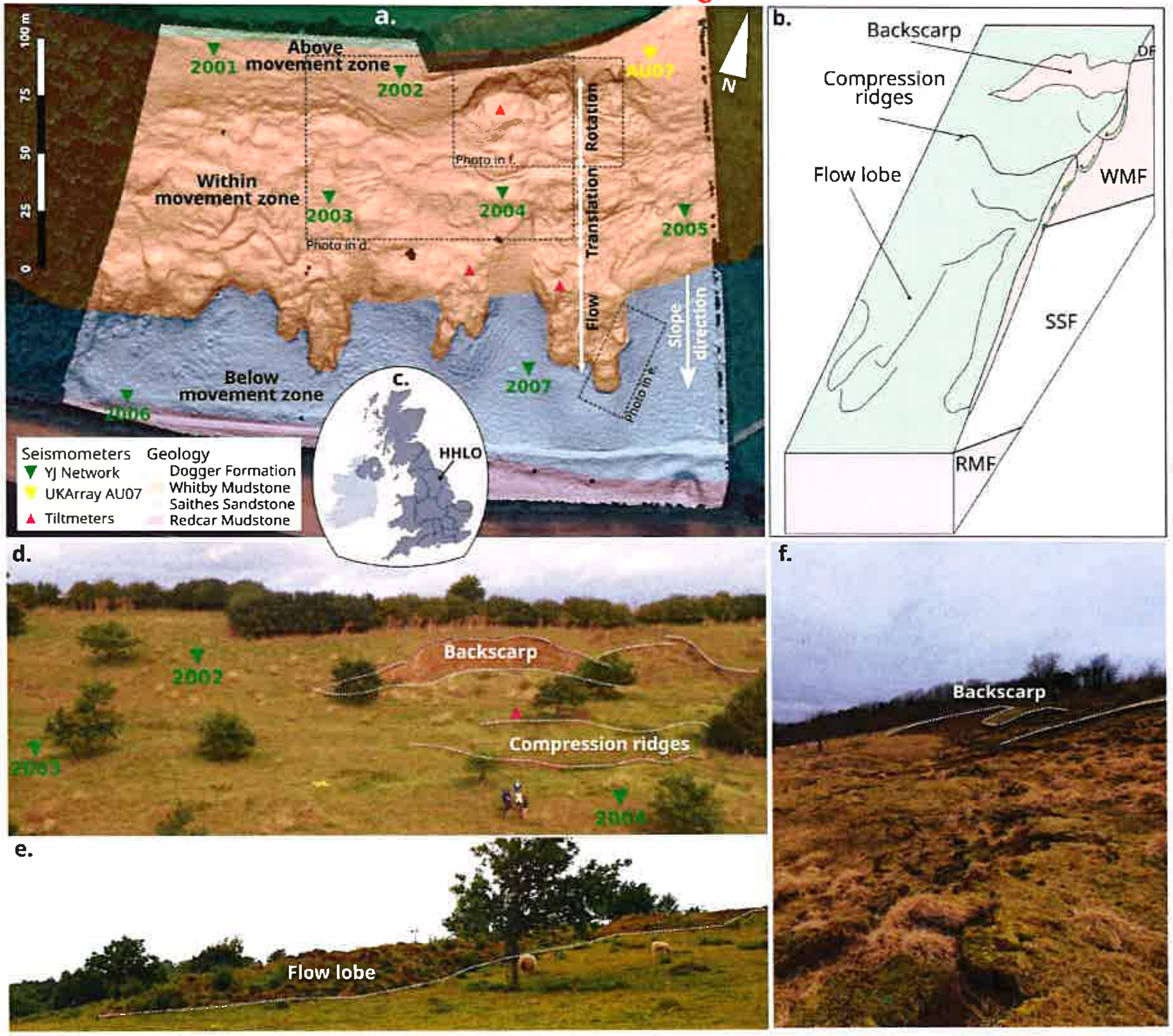


**Figure 1. a)** Map of the HHLO with major geomorphological features, underlying geology and seismometer locations. **b)** Schematic model of the geological layers and main landslide features. **c)** Location of the HHLO in the UK. **d)** Photo of the central part of the landslide, looking north. **e)** Photo of a flow lobe, looking west. **f)** Photo of surface deformation near the backscarp, looking west.

Research at the HHLO over the past two decades has primarily focused on the development of geophysical systems for monitoring slope processes to enhance early-warning capability (Whiteley et al., 2019, Whiteley et al. 2021), with a particular focus on understanding spatiotemporal variations in moisture dynamics driving slope destabilisation (Chambers et al, 2021). Key findings from geoelectrical monitoring at the HHLO include: i) estimating spatiotemporal variation in key material properties such as moisture content (Merritt et al., 2013) and matric potential (Boyd et al., 2024) can be achieved using geophysical-geotechnical petrophysical relationships, ii) slope displacements typically occur once a threshold of ~48% gravimetric moisture content (GMC) is reached, which is at a similar value to reported liquid limits for the WMF (Uhlemann et al., 2016b), and iii) changes in electrode positions can be used to recover slope movements from geoelectrical monitoring datasets (Wilkinson et al., 2016). Geoelectrical monitoring of subsurface moisture has been supported by studies also looking at corresponding slope displacements from point sensors (Uhlemann et al., 2016a), UAV surveys (Peppa et al., 2019), GPS time-series (Boyd et al., 2021), and InSAR measurements (Kelevitz, 2022).

More recently, seismic methods have been used at the HHLO to better understand how moisture dynamics influence the mechanical behaviour of saturated soils preceding failure. Whiteley et al. (2020) compared changes in seismic velocity from time-lapse active seismic refraction surveys with ground moisture and local rainfall data. They found that variations in the elastic properties of the sliding layer are linked to saturation levels (Whiteley et al., 2020). A conclusion of this study was that while repeated active surveys can provide insight into the saturation-driven mechanical variations at the HHLO, their implementation is impractical for long-term use. Hence, passive seismological monitoring was ~~has been~~ identified as a potentially viable option for long-term monitoring of slope processes, as previously demonstrated on other slow-moving landslides (Fiolleau et al., 2020; Mainsant et al., 2012; Tonnelier et al., 2013; Walter et al., 2012).

The HHLO has also been equipped with a permanent Güralp CMG-3ESP seismometer since 2015 (station AU07 of the UK Array, BGS seismic network). This dataset was used by Murray et al. (2025) to focus on detecting and characterising microseismic activity as precursors to landslide events using machine learning. Their study is particularly encouraging as it observes an increase in microseismicity prior to slope deformation. It also demonstrates that seismometers can record seismic signals originating from crack formation, propagation, or shear within the soil mass. good

### *1.3 The YJ temporary network*

The YJ (2020-2023) network, subsequently referred to as YJ, consists of seven Güralp 6TD sensors deployed at the HHLO between March 2020 and March 2022 on a loan from the UK's Natural Environment Council (NERC) Geophysical Equipment Facility (GEF) (Brisbourne, 2012). The YJ network was designed so that seismometers were installed on different landslide domains, comprising areas with different failure mechanisms (i.e., translational/creep) and underlying geology (i.e., WMF/SSF) (Table 1). These domains have been identified by previous studies considering varying displacement rates across the slope (Boyd et al., 2021) and areas of different hydrogeological conditions (Uhlemann et al., 2016b; Uhlemann et al., 2017) which allows us to test the hypothesis that seismometer setting will have an influence on the single-station analysis of seismological data. Additionally, the YJ network was designed to test the hypothesis that changes in relative surface-wave velocity, derived through cross-correlation of ambient noise, can be used to

* need to broadly state: broadband, 3C, freq range

detect variations in shear strength of landslide materials, which is critical for early-warning of slope failures.

| ID | Latitude | Longitude | Elevation (m) | Location | Geological formation unit | Landslide domain |
|---|---|---|---|---|---|---|
| 2001 | 54.11137 | -0.961835 | 100.9 | Crest | WMF | Undisturbed (above movement zone) |
| 2002 | 54.111449 | -0.96061 | 98.7 | Crest | WMF | Undisturbed (above movement zone) |
| 2003 | 54.110912 | -0.960868 | 85.9 | Mid-slope | WMF | Dormant (no active movement at time of monitoring) |
| 2004 | 54.111074 | -0.959778 | 86.7 | Mid-slope | WMF | Highly active (located beneath active rotational failure) |
| 2005 | 54.111179 | -0.958567 | 86.7 | Mid-slope | WMF | Partially active (located beneath recent rotational failures) |
| 2006 | 54.109978 | -0.96187 | 82.1 | Toe | SSF | Undisturbed (below movement zone) |
| 2007 | 54.110371 | -0.959336 | 59.6 | Toe | SSF | Undisturbed (between active flow lobes of landslide) |

**Table 1.** Properties of the station locations in terms of geology and landslide domain at the HHLO.

## 2. Instrument deployment

The seven Güralp 6TD seismometers were deployed between 9 and 11 March 2020 following the SEIS-UK deployment procedure (Lane et al., 2020). The seismometers were buried 40 cm below ground level in a pit filled with sand. Each station was powered by a 12V battery installed in a metal box recharged by two 20W solar panels mounted on a wooden frame. The metal box was customised by BGS to allow the connection of two lengths of hose via plastic push-fit connectors into the storage box. This provided extra protection for the cabling from livestock and moisture ingress (Figure 2).

The Güralp 6TDs were configured to record at 200 Hz. With this configuration, the instruments could store up to four months of data. Eight service runs were completed on schedule, with the exception of one run in Spring 2021 which was delayed due to the impact of Covid-19 on staff availability (Figure 3). This service run was conducted a few days after the data storage disks reached capacity. Details of activities during deployment, on each service run and during decommission were recorded on service sheets, which were scanned and archived.

* figure captions should stand alone, expand

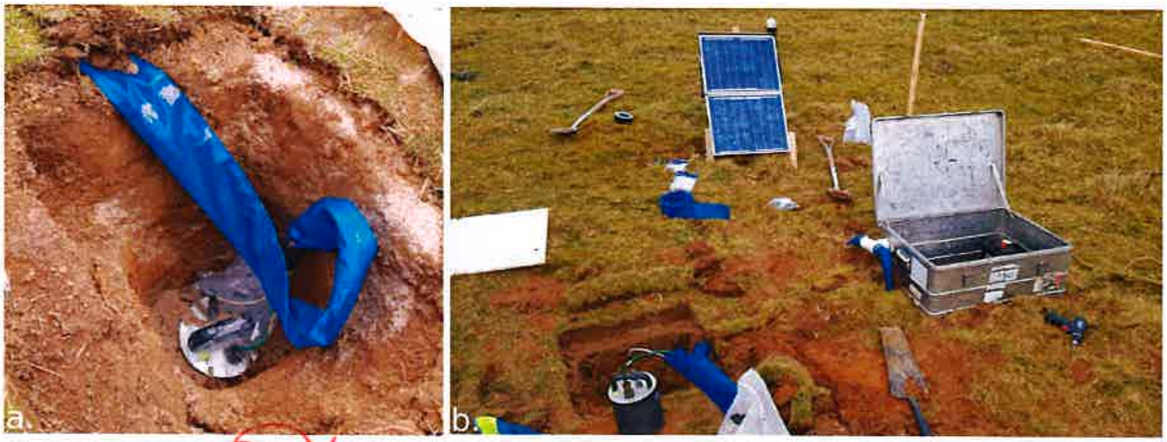


**Figure 2. a**) Typical 6TD installation * at the HHLO site. **b**) Wider station setup showing solar panels and customised ~~storage box for~~ housing housing battery, data storage disk and cable connection box.

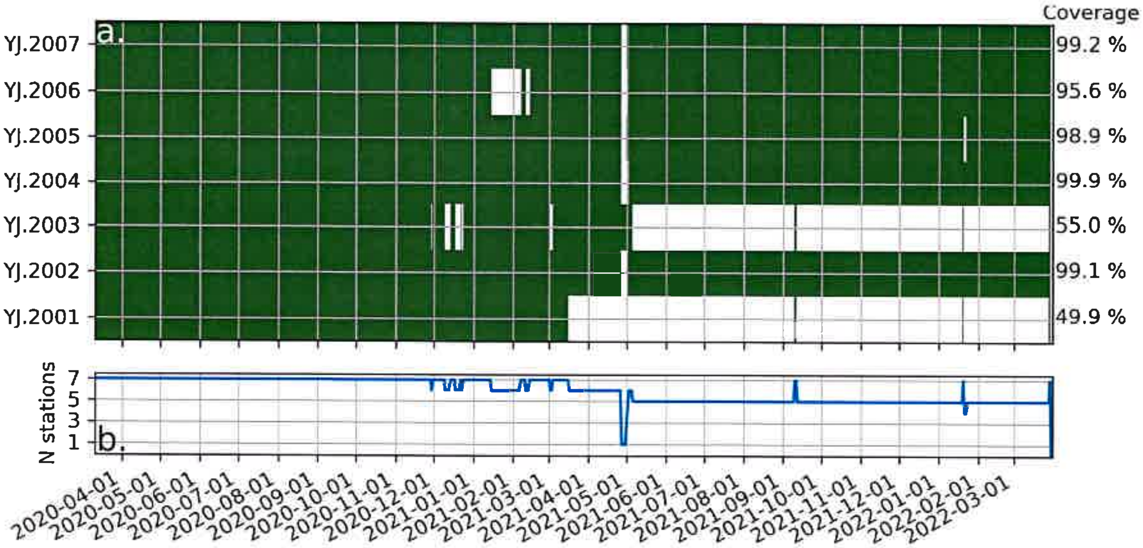


**Figure 3. a**) Data availability per station. **b**) Number of stations available per day.

One seismometer (YJ.2004) failed during the monitoring period (in January 2021), likely due to extensive subsurface flooding ~~of the installation~~, and a replacement sensor was ~~provided by SEIS-UK and~~ deployed in February 2021. Two stations (YJ.2001 and YJ.2003) had persistently failed shortly after service runs, with issues commencing in winter and spring 2021, respectively. These issues were associated with blown fuses, although no exact cause was determined, but moisture reaching the electronic boards was suspected. Despite remediation attempts, including fuse replacement, neither station was able to record data for significant lengths of time after these dates. Five of the seven 6TDs had >95% data coverage, with network-wide data coverage being 85% for the two-year monitoring period (Figure 3). The reduced data coverage in the second year (with only >70% data coverage) is expected to have a relatively minimal impact on the data investigation since at least one seasonal cycle ~~has been~~ was captured at >95% data coverage, and at least one sensor in each landslide domain remained active throughout the monitoring period.

## 3. Description of obtained data

### *3.1 Repository details*

Seismic data are archived on the SEIS-UK Octomore data management system and IRIS data management centre with network code YJ 2020 - 2023 (Watlet et al., 2020a), under the name of Yorkshire Landslide Observatory (YoLO).

### *3.2 Data quality and noise level*

– interpretation, stick to facts

The quality of recorded data is acceptable, with noise levels for all stations falling between the low- and high-noise model curves of Peterson (1993). All stations show relatively high noise levels at low frequencies, corresponding to the secondary microseism (periods of 1 to 3 s). The secondary microseism is generated by ocean wave interactions, and so stronger intensity can be expected ~~on an island such as~~ in Great Britain (Figure 4) due to the close proximity to the ocean. Seasonality in secondary microseisms is also evident, with periods of elevated low-frequency noise levels (0.1 to 0.5 Hz) reflecting the increased frequency of winter storms, typically occurring from October to March in the UK.

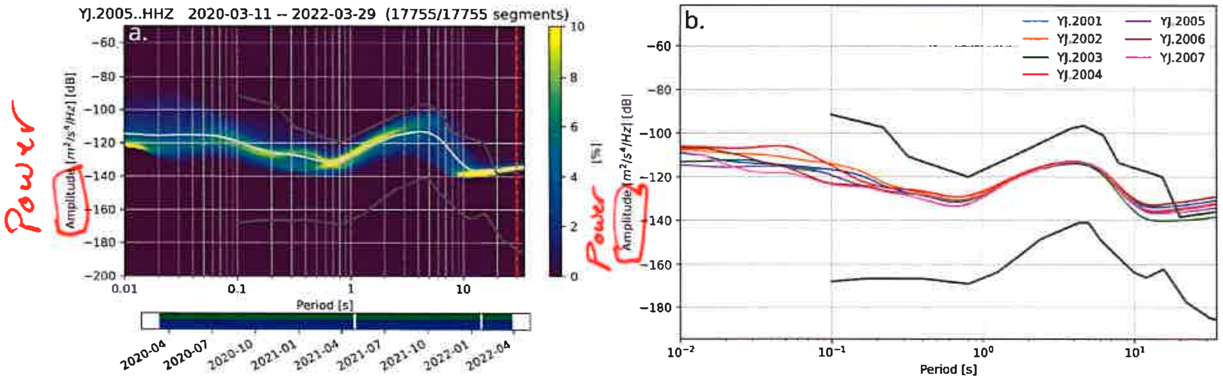


**Figure 4. a**) Vertical component probabilistic power spectral densities (PPSD) plot for the monitoring period for station YJ.2005. Grey lines indicate the low and high noise models of Peterson (1993), the red line marks the upper period bound of the 6TD response (30s). **b**) Average PPSD for each station.

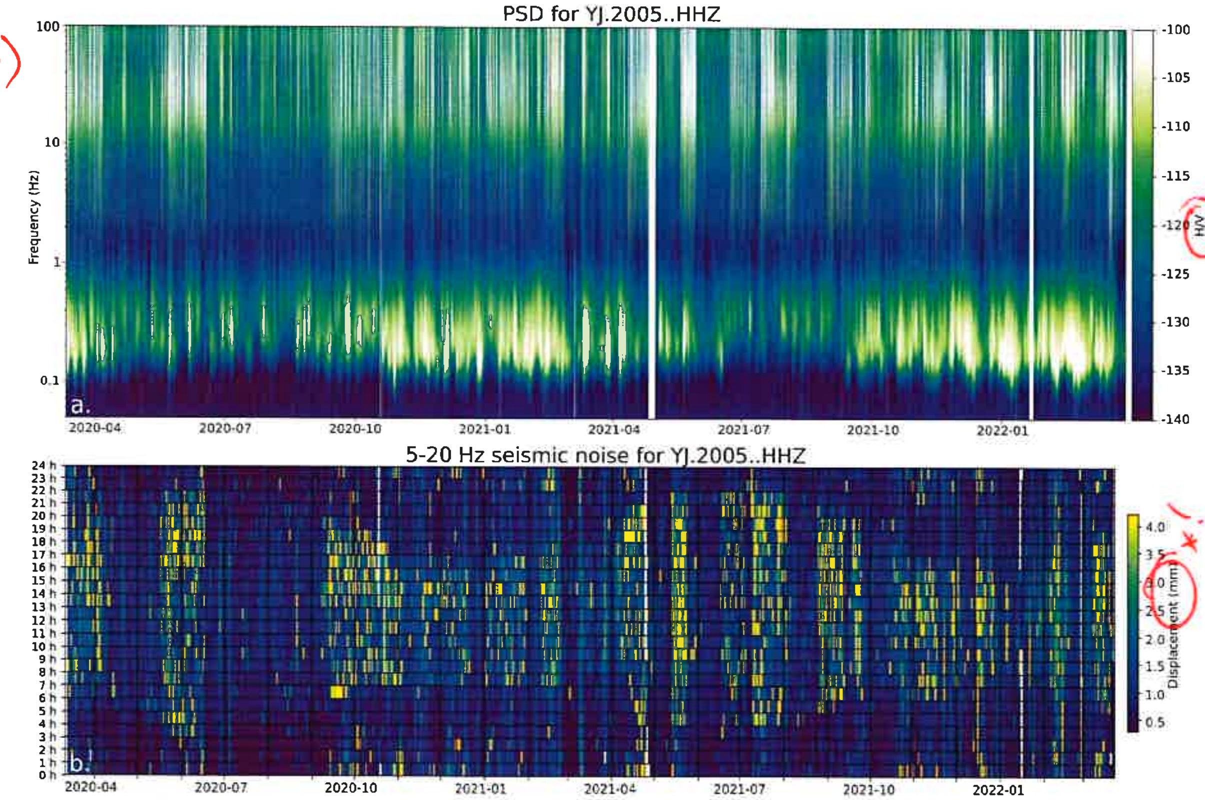
The HHLO site is relatively remote, located in a rural area approximately 20 km away from the closest city, York. Higher frequency noise is mainly influenced by farming activity, and especially the intermittent presence of sheep in the field, and to a smaller extent to a highway passing ~7 km south-east. The site is also frequently exposed to wind which ~~might also~~ can contribute to increased noise levels at higher frequencies. The farming source of the high frequency noise is evidenced by

~~significant~~ increases in noise intensity during periods of sheep breeding (Figure 5), which presents an interesting but challenging noise source to consider in the processing steps. A seasonal effect in the high-frequency noise is also clearly visible in Figure 5b, with increased noise levels corresponding to daylight hours, which is attributed to reduced sheep activity at night.

High frequency noise slightly varies in intensity across the network (Figure 4), with station YJ.2004 being noisier in periods below 0.1 - 0.05 s (10 - 20 Hz) than other stations. This elevated noise level could be linked to YJ.2004 location being in an active zone of the landslide.

a)

b)



dB? *

*!

**Figure 5. a**) Spectrogram of ambient noise over time compiled from hourly averaged PSD for YJ.2005. **b**) Temporal evolution of high-frequency (5 to 25 Hz) ambient noise displayed as a matrix plot. Each row corresponds to an hour of data (produced using SeismoRMS by Lecocq et al., 2020). Higher frequency noise is most often linked with sheep presence in the field.

* what does 4mm displacement relate to? That's a huge value, is it time integrated? ~~Method not described~~

## 4. Preliminary interpretations

### *4.1 Seismic event analysis*

We applied a series of ~~classic~~ STA/LTA (Short-Term Average/Long-Term Average) filters on the YJ network inventory and detected a range of seismic events, of which some have a local source (Watlet et al., 2020b). Amongst events attributed to local environmental noise sources (farming activities, livestock on site, etc.), one signal is thought to be more clearly related to the landslide activity (Figure 6). This event type, usually recorded on several of the stations, was observed on various occasions (> 100 occurrences), mainly in dry conditions. It has a short duration (<2 s) and shows harmonic-like frequency components (in the 7-25 Hz band). We formulate the hypothesis that this type of events is linked to the opening of fractures during periods of clay-shrinkage. Many deep cracks (>0.5 m deep) can indeed be observed on the clay-rich slope in dry conditions, often extending over several meters laterally (see Figure S1 of the Supplementary Material for an example).

The harmonic frequencies generated by these events remain difficult to explain without more detailed source analyses, which lie beyond the scope of this data-based report, but can be supported by analogues in the literature. Similar short-duration, narrow-band signals have been reported during brittle failure and crack opening in landslide contexts, as well as in analogous environments. Vouillamoz et al. (2018) reported short-duration (< 2 s) quake-like signals associated with landslide activity (termed slidequakes). While they only observed harmonic components in longer events at the Super-Sauze landslide, other studies have highlighted the potential for finite fractures to resonate or oscillate during rapid opening. Sicking and Malin (2019) showed that fracture openings can generate short-duration energy pulses and harmonic resonances of the entire fracture, and Chouet (1986) discussed the resonant modes of cracks, demonstrating that modeled cracks produce multiple discrete frequency peaks whose frequencies depend on crack length and boundary stiffness. Such modeling experiments seem transferable to our landslide context and could explain the harmonic frequencies of this particular event. A more detailed spectral and source-mechanism analysis would be required to confirm this interpretation.

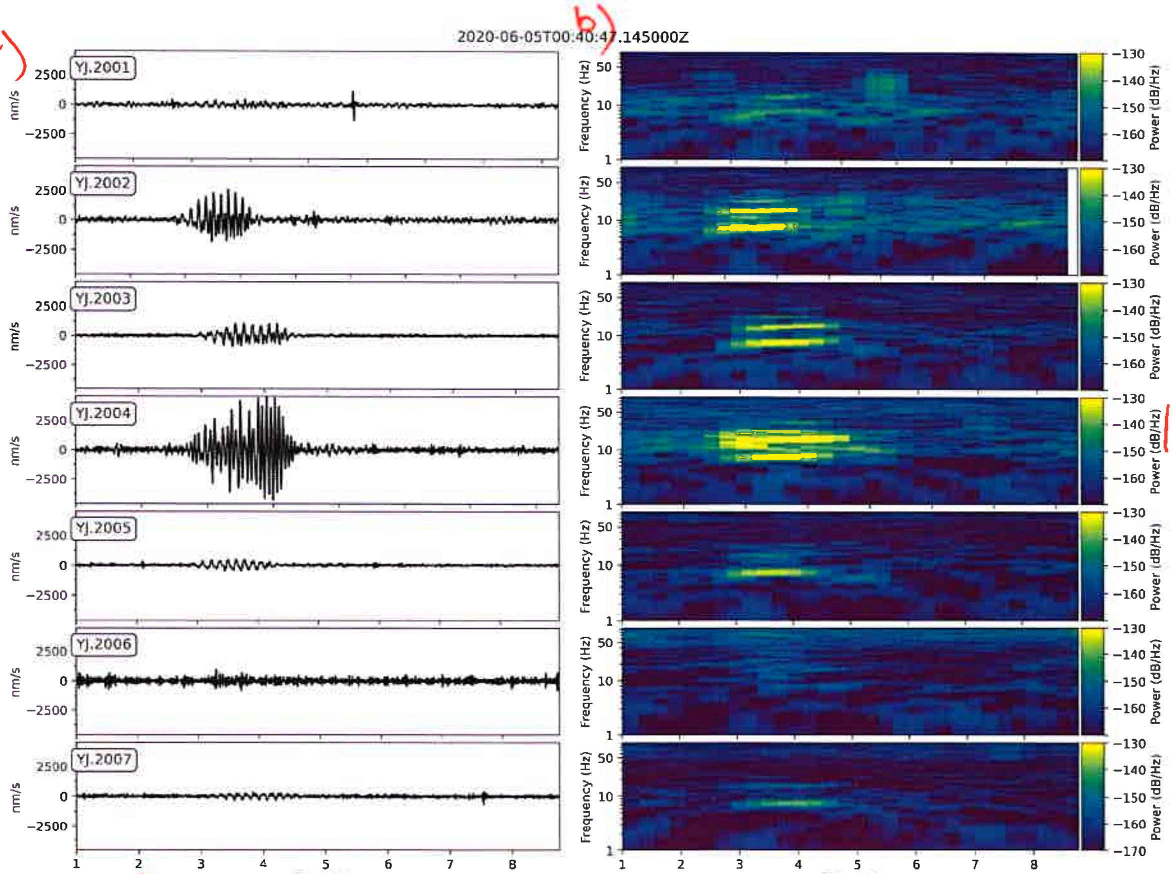
Furthermore, the fact that mainly brittle deformation generates energy high enough to be detectable with conventional STA/LTA approaches seems plausible. More ductile movements in highly saturated clay materials are likely to be less efficient at radiating seismic energy. More advanced, machine-learning algorithms are also likely to help detect smaller local events potentially associated with landslide activity. Recently, a machine-learning event-detection approach was successfully trialled at the HHLO site by Murray et al. (2025), based on the single-station AU07 broadband sensor from the UKArray network installed at the site. In this study, ~~they~~ Murray et al (2025) detected a significant number of events preceding landslide movement, promoting promising expectations for a similar approach to be applied in the future to the YJ network, thereby providing improved spatial information on landslide-related seismic activity.

Nonetheless, there has been discussion regarding the potential for clay shrinkage to act as a ~~pre~~conditioning factor for ~~subsequent~~ landslide movement, particularly in clay-rich slopes

("pre" conditioning would be the presence of clay)

(Krzeminska et al., 2013; Meisina, 2004). Increased opening of cracks under dry conditions may promote water infiltration rather than run-off during subsequent re-wetting periods, potentially explaining localised zones of elevated moisture that could drive slope failure. Techniques capable of detecting crack openings during the drying process could therefore help identify areas of interest where slope movement is more likely during later wet periods. We therefore consider the event type presented in Fig. 6 to be relevant for landslide monitoring and that future studies could build up on these findings to investigate slope-scale clay shrinkage in more detail, potentially linked with larger scale information on slope deformation. good

a) b)



c: dB/Hz → x

b)

**Figure 6.** ~~Left~~ a): Example seismic events attributed to crack generation with vertical component traces. ~~Right~~ b): Accompanying spectrograms.

### *4.2 Tilt*

In the landslide context, ~~looking at~~ analysis of tilt from the internal masses of ~~the~~ seismometers may provide insight~~ful~~ ~~information on~~ into ongoing slope deformation. Conventional tiltmeters typically capture near-surface rotational movement, whereas our the goal ~~here~~ is to assess whether seismic traces can also be used to infer subsurface tilt generated by slope deformation processes.

The sensor mass position outputs recorded by the ~~Taurus~~ datalogger ~~(M8, M9, M0 files)~~, showed interesting variability across the ~~whole~~ monitoring period. However, these data are difficult to interpret in raw counts and are not publicly available on the EarthScope repository. We therefore focused on extracting tilt information directly from the seismic traces, following the approach of ~~developed in~~ Wenner et al. (2022). In their study, tilt is retrieved ~~they retrieve the tilt signal~~ by applying a very low-frequency filter to the seismic trace, followed by a conversion from counts to tilt angles using the instrument response. For the very low-frequency data (periods below the instrument's lower corner frequency), this conversion requires integrating the digitizer output signal and subsequently scaling the resulting time series by a factor that includes the instrument's corner frequency, sensitivity, and the negative gravitational acceleration. While Wenner et al. (2022) focused on short-duration tilt episodes, our analysis extends this approach to both shorter-term tilt variations (e.g., during an attested slope movement event) and longer-term, seasonal tilt.

Therefore, we ~~slightly~~ adapted the approach of Wenner et al. (2022) by applying first a low-pass filter below 60 s (i.e., corner frequency of the Guralp 6TDs) instead of a band pass filter between the corner frequency and 2 hrs, to retain the lowest period tilt. Then we apply conversion before detrending and correcting for steps across data gaps. This approach assumes continuous, linear instrumental drift. A comparison between the retrieved tilt data and the internal mass position time series (Figure S2 of the Supplementary Material) highlights correlated signatures, with amplitude differences likely related to the conversion from counts to degrees and imperfect detrending. Our approach assumes no net tilt change between the start and end of the trace, meaning that any long-term ~~linear~~ trend is suppressed, which is a limitation when investigating seasonal-scale tilt.

Instrumental performance also affected tilt recovery for some stations. For instance, at YJ.2004, a datalogger failure in February 2021 led to replacement of the seismometer, and the low-frequency response before that period seems to have been limited by a digitiser issue. For YJ.2001, a levelling problem likely caused rapid out-of-range mass positions, ~~resulting in a strong polynomial trend~~, preventing reliable tilt retrieval.

Significant tilt changes are observed only for sensors above and within the movement zone, while stable-ground stations (YJ.2006, YJ.2007) show only minor seasonal tilt, which we attribute to thermoelastic processes. For the other stations, individual sensor tilts, whose components were rotated in downslope and cross-slope directions, show both a seasonal~~ity~~ signal (mainly visible for YJ.2002 and YJ.2004) and increased short-term variability between May and October 2020, typically the drier months at the HHLO (Figure 7). ✓

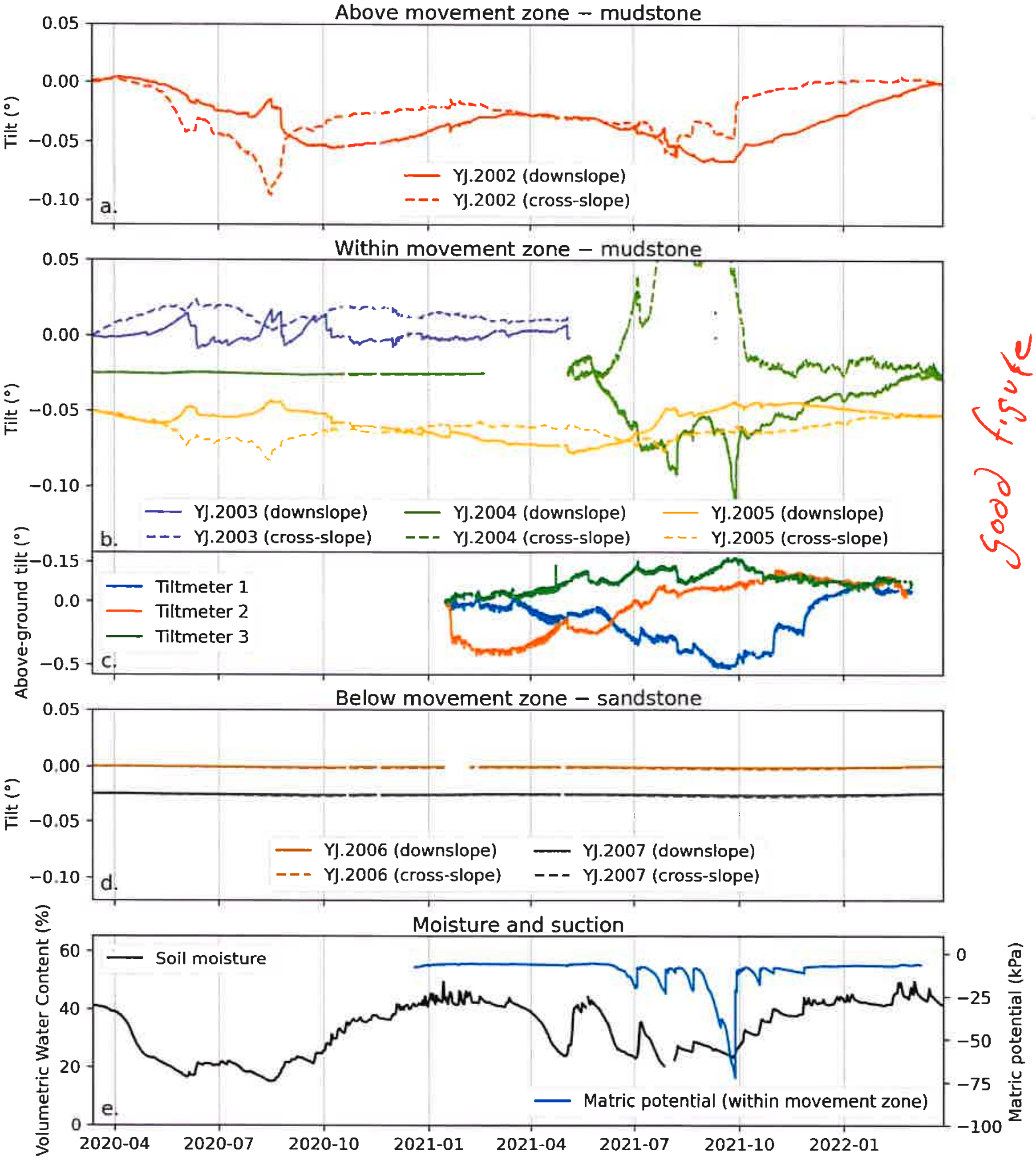
By early 2021, three mast-mounted tiltmeters were installed in the active movement zone (Figure 7d). The tiltmeter data show no consistent general trend at the seasonal scale, but indicate that local morphological features of the slope, such as nearby compression ridges, or position on the slope, strongly influences tilt direction and magnitude. The seismically derived tilt data agree well with these above-ground tilt measurements. Both datasets confirm that tilt is not only recorded during active movement but may also be influenced by shrink–swell processes. Comparison of tilt variations with soil moisture and matric potential data shows a transition from slow, continuous drift to more rapid, pronounced tilt fluctuations during periods of depleted matric potential. This suggests a possible link between desiccation cracking and sensor stability at the HHLO. ✓

Tilt induced by clay shrink–swell is likely linked to volume changes in the disturbed upper clay layer (~2 m), where desiccation cracking may generate local rotational deformation depending on the morphology of the upper layer most affected by volume change. For instance, zones close to compression ridges are expected to accommodate volume change differently than the flow lobe~~s~~ areas. Repeated LiDAR scans of the slope have ~~already~~ previously highlighted seasonal uplift of several tens of centimetres during the wet months (Watlet et al., 2024) at the HHLO. Kelevitz et al. (2022) investigated slope deformation at the HHLO via long-term InSAR analyses and found that seasonal displacement was strongly correlated with volumetric water content. They suggest that these vertical changes are driven by volumetric deformation linked to the wetting and drying of the mudstone. Using repeated Seismic Refraction Tomography surveys, Whiteley et al. (2020) observed significant temporal variations in Poisson's ratio ~~(i.e. the ratio of lateral to axial strain)~~ within the surface sliding layer, ~~essentially~~ indicating bulk volumetric change. Observations in these ~~three~~ studies tend to confirm slope-scale shrink-swell processes, and support the seasonality observed in our seismically-derived tilt timeseries.

We also examined whether the seismically derived tilt data captured deformation during the main slope movement event that occurred during the YJ network monitoring period (20-21 January 2021; Watlet et al., 2024; Figure 8). This relatively minor event, as compared to the documented history of ~~the~~ landslide activity, resulted in slope displacement of up to 0.5 m mainly concentrated in the backscarp region. In the absence of meaningful tilt data from YJ.2004 at that time, only YJ.2002 (Figure 1) recorded significant tilt variation, indicating that the event induced tilt signals above the zones where slope displacement occurred, and also confirms that the retrieved tilt data from the seismic trace is effective at tracking slope movement.

(or move to conclusion)

~~Overall, our tilt analysis supports the use of broadband seismometers as complementary tools for monitoring both short-term deformation events and longer-term seasonal tilt processes in clay-rich landslides~~.



Good figure

**Figure 7.** Seismically-derived tilt data for above movement zone (a), within movement zone (b) and below movement zone (c), both for the downslope and cross-slope components. These are compared with above-ground tilt data recorded by tiltmeters mounted on masts (50 cm above ground) from January 2021 (d), and soil moisture and matric potential data (e).

in the active zone

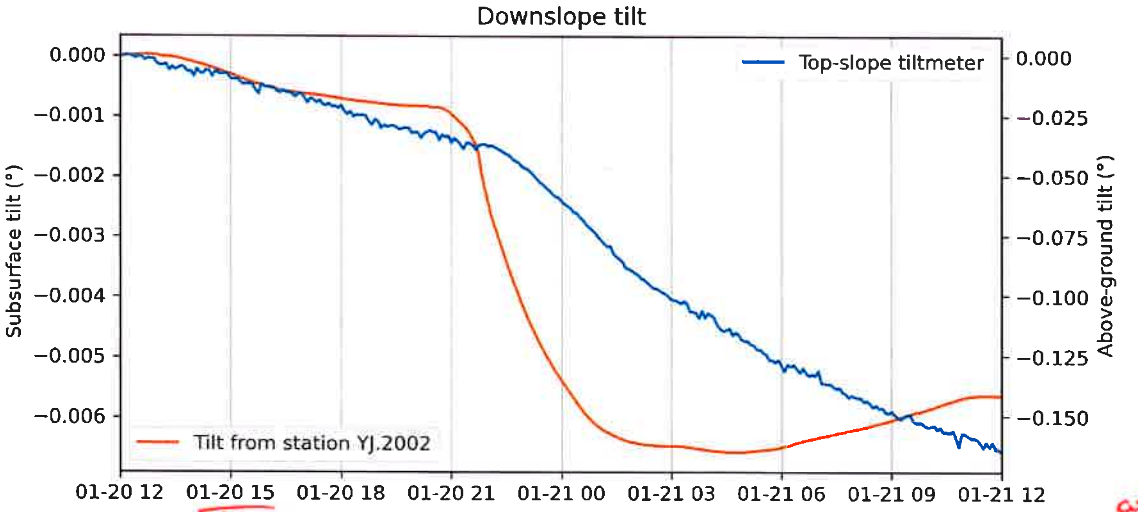


**Figure 8**: ~~Comparing~~ T tilt signal s observed during attested slope movement for seismically-derived tilt ~~from~~ at station YJ.2002 and top-slope tiltmeter.

### *4.3 Continuous H/V observations*

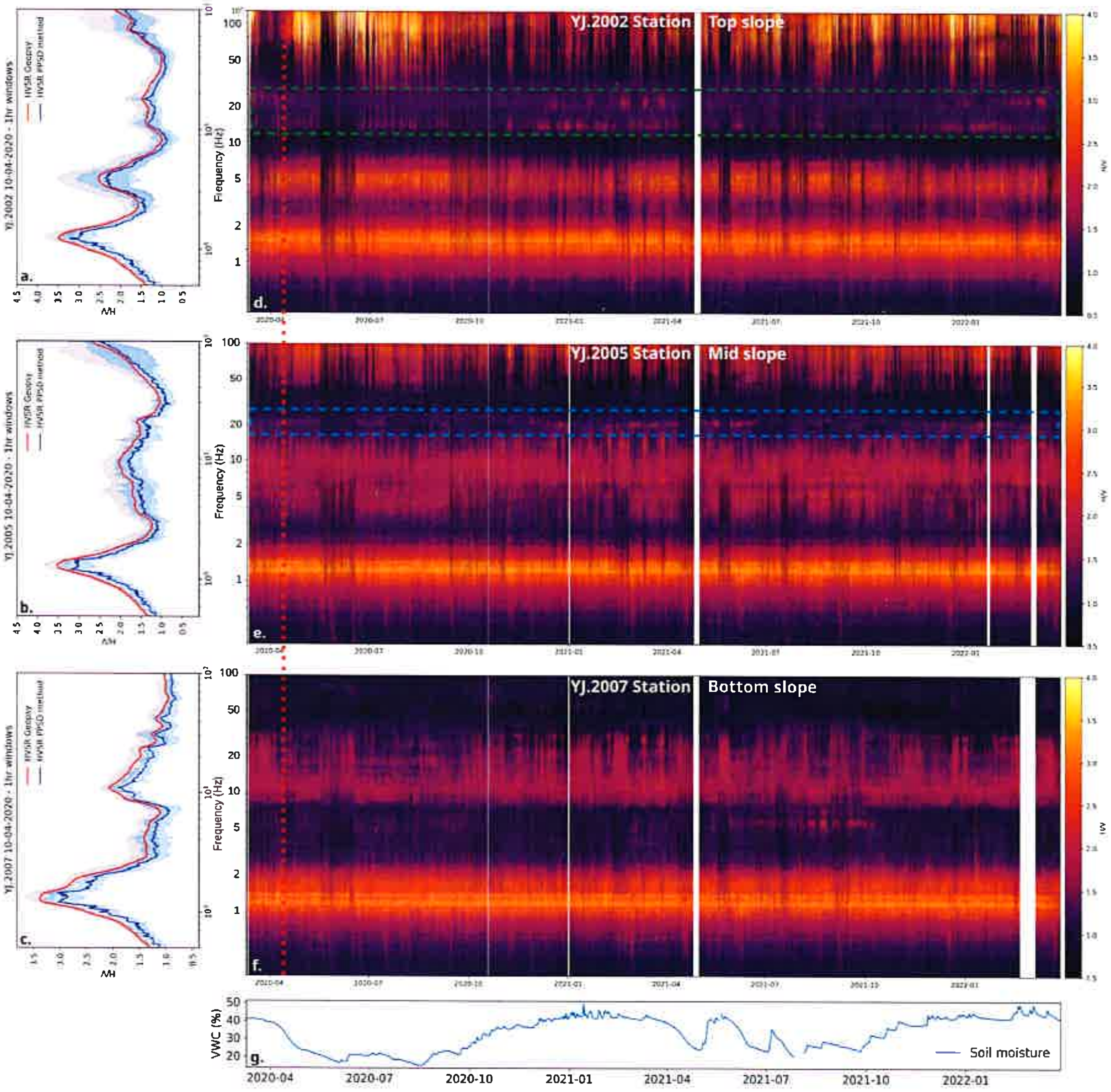
We computed temporal horizontal-to-vertical spectral ratios (H/V ratios) (Nakamura, 1989) based on the ratios between hourly power spectral density (PSD) spectrograms of the horizontal and vertical components, in a similar way as van Ginkel et al. (2024). The H/V ratios $a$ are determined as follows:

$$a=\frac{\frac{\sqrt{10^{\frac{E}{10}}}+\sqrt{10^{\frac{N}{10}}}}{2}}{\sqrt{10^{\frac{Z}{20}}}} \quad \text{(Eq. 1)}$$

Where $E$, $N$ and $Z$ are the hourly PSD expressed in dB for the east, north and vertical components respectively.

Figure 9a, 9b ~~and~~ 9c shows that our approach delivers similar H/V plots as those computed with the Geopsy software (Wathelet et al., 2020) for a 1-hour time window. Temporal H/V spectrograms display the ~~temporal~~ evolution of hourly H/V plots, ~~They~~ provid~~e~~ing information on the temporal stability and shifts of major and minor frequency peaks ~~(Figure 9)~~. Temporal H/V spectrograms are useful to study the subsurface changes ~~underneath~~ at each station.

On the YJ network dataset, the primary peak at ~1.2 Hz is relatively stable across the network and corresponds to a regional impedance boundary at depth (>150 m deep). A secondary peak at ~4.5 Hz for YJ.2002 (top slope) and ~10Hz for YJ.2005 (mid slope) ~~and~~ is thought to reflect the WMF-SSF interface boundary. Other secondary peaks at higher frequencies are also visible and appear seasonally (e.g. in the 10-25 Hz frequency band for YJ.2002), which can be related to the occurrence of temporary perched water tables in winter, as suggested by Uhlemann et al. (2016a). Using seismic refraction tomography (SRT), Uhlemann et al. (2016b) imaged clear contrasts in the P- and S-wave distributions at the interface between undisturbed and disturbed materials in the active part of the landslide, as well as between mudstone and sandstone layers. More pronounced impedance contrasts could occur in summer between relatively drier mudstone and wetter underlying sandstone, contributing to explain the occurrence of seasonal H/V peaks.



watch very small font sizes

**Figure 9.** Comparison between H/V ratios computed using Geopsy software (Wathelet et al., 2020) and the probabilistic power spectral densities PPSD ratio method for station YJ.2002 **(a)**, YJ.2005 **(b)**, and YJ.2007 **(c)** respectively, as calculated on a 1 hour period on the 10-04-2020. d, e, f: Spectrograms of H/V ratios over time for station YJ.2002 **(d)**, YJ.2005 **(e)** and YJ.2007 **(f)**, as well as soil moisture recorded at 10 cm by the

COSMOS-UK station at Hollin Hill (g). Green and blue dashed boxes highlight frequency bands 10-20 Hz and 18-22 Hz respectively. Red dashed line indicates day sampled in a, b and c subplots.

Data for some of the stations also experience shifts in the secondary peak frequency (e.g. in the 18-22 Hz frequency band for YJ.2005), which may be linked to shear wave velocity variations in the upper layers due to changes in moisture content. Whiteley et al. (2020) investigated the temporal variations in P- and S- wave velocity inferred from repeated SRT surveys at the HHLO and highlighted a seasonal shift in Vs comprised between 100 and 150 m/s in the disturbed material of the sliding layer. Similar observations were identified in a different slope context by Guo et al. (2023). The fact that such shifts are present on data from YJ.2005 and not as clearly on YJ.2002 could be linked to their respective locations on the landslide. YJ.2005 is ~~indeed~~ sited on the reworked WMF mudstone materials, which experience larger seasonal amplitudes in wetting and drying processes than for the above movement zone of the WMF mudstone where YJ.2002 sits.

~~These~~ observed temporal variations in H/V ratios have implications for slope stability assessment. H/V ratios are linked to shear wave velocity (Tsai, 1970), which is an important variable in the understanding of material behaviour via determination of elastic moduli, such as the shear modulus (e.g. Carrière et al., 2018). Slope stability is also strongly linked with the degree of saturation in the shallow subsurface (Huang et al., 2012), which explains the observed correlation between H/V ratio changes and soil moisture at the HHLO.

### *4.4 Ambient noise cross-correlation and velocity change*

We investigated...

~~were~~

Changes in seismic velocity ~~are investigated~~ using ambient noise cross-correlation. Ambient noise data were processed with MSNoise (Lecocq et al., 2014), broadly following the steps described by (Bensen et al., 2007). Hourly seismograms were split into 60s long segments which were cross correlated between each possible pair (21 pairs when all stations were recording) for the ZZ, EE and NN components. The cross-correlations were stacked for each day. The seismic velocity change was computed following the moving window cross-spectral (MWCS) technique (Clarke et al., 2011) on the coda of the cross-correlations. Seismic velocity changes (*dv/v*) are derived from relative travel-time variations (dt/t) detected in a sliding window of the coda wave.

Preliminary results on specific frequency bands suggest a link between soil moisture and velocity change (Figure 10), with velocity decreasing as soil dryness decreases. Further analyses on a broader range of frequency bands should be considered following the approach presented by Oakley et al. (2021). These further analyses could include rotation into a coordinate system aligned with the local surface slope, because high-frequency surface waves are expected to follow the surface topography. Potential thermo-elastic mechanisms linked with changes in soil temperature could also be further investigated.

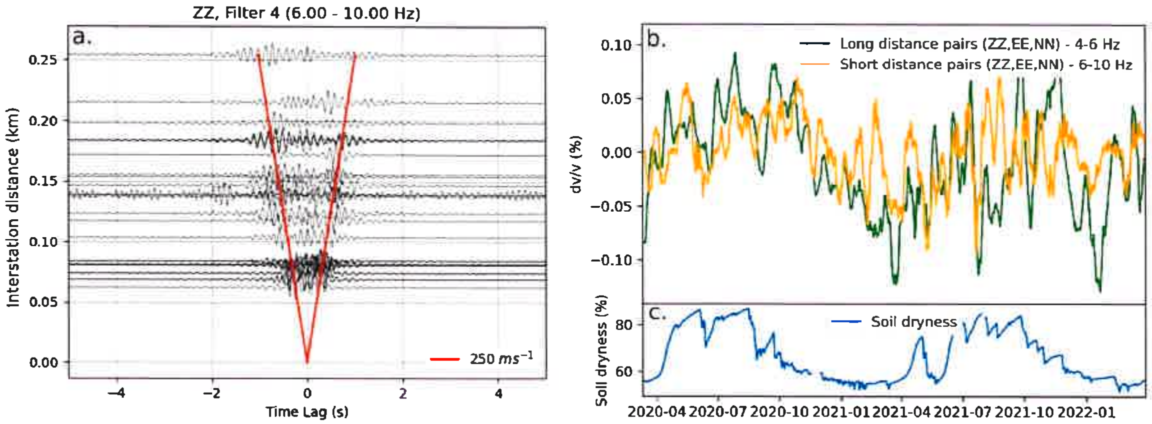


**Figure 10. a**) Average cross correlation functions for each pair displayed as a function of the interstation distance (for the 6-10 Hz band). **b**) Example *dv/v* plot for long distance (> 150 m) and short distance (< 150 m) pairs at two selected frequency bands. **c**) Soil dryness (inverse of soil moisture).

### *4.5 Discussion of preliminary observations*

Wetting and drying processes within clay materials are thought to drive landslide activity and slope displacement at Hollin Hill (Uhlemann et al., 2017). Our observations suggest that changes in soil moisture~~,~~ and pore water pressure at shallow depth impact the seismic signals recorded by the YJ network. Clay shrinkage associated with decreasing water content generates tilt on the horizontal masses of the seismometers. Desiccation and large crack openings seem to generate specific seismic events, some of which are recorded throughout the network.

Conversely, temporal H/V ratios spectrograms indicate that secondary H/V peaks vary both in frequency and intensity and are thought to be linked to impedance contrasts and seismic velocities fluctuating in the shallow subsurface due to changes in soil moisture and the occurrence of seasonal perched water tables. Further investigating the links between H/V ratios and slope stability could be useful in a landslide monitoring context. For instance, shear-wave velocity profiles could be extracted from H/V ratios inversions, and used to derive temporal changes in Poisson's ratios. Seismic interferometry has also been trialled on data from the network and similarly highlights changes in seismic velocities in medium to high frequency bands, likely linked to changes in soil moisture.

The primary aim of this study is to introduce and promote the dataset from the YJ network, and the authors recognise that there are many limitations in the analysis of the data presented in this data-based report. Key limitations include: i) absence of in-depth noise analysis, ii) impact of failed sensors on network wide analyses, iii) further investigation into the drivers of sensor tilt at the site and an evaluation of the use of this data for monitoring landslide processes in and of itself. A notable limitation of the tilt analysis is the observation that rapid, out-of-range mass positions in the sensors can prevent reliable retrieval of the tilt angles, which is a likely scenario when deploying sensors to active slopes.

Overall, our preliminary observations suggest that, subject to further investigations, seismic records from the YJ network show a strong potential to shed new light on the link between landslide activity and seismic activity in clay-rich, slow-moving landslides. Challenges related to tilting sensors, anthropogenic (and sheep) noise variations, as well as source noise location analyses need to be addressed in order to further determine the reliability of the data throughout the monitoring period. However, some limitations could be overcome by deploying a greater number of seismic sensors, such as using seismic node arrays, or by using more robust instruments, such as a new generation of seismometers less sensitive to tilt (e.g., Reis et al., 2021). Table 2 summarises several avenues for future work based on the YJ network dataset, highlighting where further analysis could provide additional insight into slope-scale processes. These include improved characterisation of slidequake signals, a deeper investigation of tilt–moisture interactions, automated detection of temporal changes in H/V ratios, and more advanced ambient-noise cross-correlation approaches.

good

| Topic | Perspective for future work~~s~~ |
|---|---|
| **Slidequakes detection and analysis** | • Perform detailed spectral analysis to characterize signal frequency content (as performed in Murray et al. (2025)).<br>• Compare with known seismic signatures of landslides.<br>• Investigate correlations between signal occurrence and other landslide-related changes (e.g., slope displacement, soil moisture). |
| **Tilt data and relationships with soil moisture** | • Expand research analysis on desiccation cracking influencing tilt signals, potentially including laboratory experiments.<br>• Identify and account for other factors that may affect tilt measurements. |
| **H/V ratio and seasonal variations** | • Develop automated detection of temporal shifts in H/V peaks.<br>• Extract Vs profiles via H/V ratios inversions and relate to Poisson's ratios estimations.<br>• Investigate how H/V ratio variations relate to slope stability. |
| **Ambient noise cross-correlation analysis** | • Expand the analysis to incorporate wavelet-based dv/v estimation<br>• Conduct a more quantitative analysis of the relationship between soil moisture and velocity change. |

*Table 2: Perspective for future work to be conducted on the YJ network dataset and their implications for landslide research.*

## 5. Conclusions

From March 2020 to March 2022, we operated the YJ network composed of seven Güralp 6TD seismometers, provided by SEIS-UK, at the HHLO to monitor subsurface processes. This dataset has demonstrated the potential for the application of approaches typically applied to monitoring large-scale geohazards (volcanoes, earthquakes, etc.) to investigate shallow, hydrologically controlled landslides. The~~se~~ investigation approaches include: i) the use of seismic event detection (STA/LTA filters) to identify crack generation during dry summers, ii) seasonal tilt observations, iii) determination of continuous H/V profiles to monitor changes in resonance frequencies associated with hydrologically controlled impedance contrasts and velocity changes, and iv) ambient noise cross-correlation to obtain broad changes in near-surface velocity associated with soil wetting and drying. Although the analysis of data from this network is preliminary, we show that ~~the~~ soil moisture dynamics influence the mechanical behaviour of landslide-prone materials at the site, an observation consistent with ~~those made in~~ other recent studies (e.g., Watlet et al., 2024; Whiteley et al., 2020; Ouellet et al., 2024).

One main motivation of this data-based report was to present the seismic dataset and highlight the potential for further investigations by fellow seismologists. These may include AI-based approaches to detect microseismic events generated by landslide activity (e.g., Murray et al., 2025). The tilt signals measured by the seismometers have shown their potential to investigate slope-scale seasonal shrink-swell processes and could be used in combination with other slope deformation sensors and techniques to further validate the observations and the implications on landslide activity. The temporal H/V analyses are ~~quite~~ promising and could be combined with analyses on azimuthal dependence and temporal variability in the secondary peak frequencies for instance to investigate potential links of resonance direction and slip surfaces, in a similar way as in Guillemot et al. (2024). Looking at the inverse of H/V ratios (V/H ratios) could also be considered to improve the detection of impedance anomalies linked with zones of elevated moisture, locally close to saturation, which can have a strong impact on the landslide activity. Finally, implementing more advanced seismic interferometry analyses, for instance including wavelet transforms, could be more helpful to investigate the frequency bands more subject to changes in seismic velocities throughout the slope. Data from the YJ network will also be useful to compare and contrast seismic measurements made by a distributed acoustic sensing (DAS) system that was deployed at the site broadly across the same time period (Ouellet et al., 2024; Watlet et al., 2024). A recommendation for future deployments of this nature would be to explore the use of large-n nodal systems that would be able to provide much higher spatial resolution and with lower deployment effort, although the suitability of such as deployment for long-term monitoring would be less favourable.

# Responses to review round 2 of “Seismic response of a slow-moving landslide: exploring data from two years of seismic monitoring at the Hollin Hill Landslide Observatory (UK)

Dear Editor,

Thank you very much for handling the review of our manuscript. We are really pleased that our efforts to improve it was appreciated by both reviewers. We have now integrated the remaining minor points in this updated version. We have also revised the Data and Code Availability section to include a clear reference to Zenodo, where additional data (beyond the seismic data archived on IRIS) and the custom codes supporting this manuscript have now been deposited.

**Reviewer A**

I thank the authors for their detailed response to my previous comments. I agree that it is difficult to find the right balance between presenting a dataset and offering robust and interesting first interpretations of that dataset, and I think the revised manuscript is a strong step forward in the right direction toward that balance. The figures, presentation and overall analysis are much improved. As I am satisfied with the author’s response to the reviewer comments, I had a look at the manuscript freshly again and offer some final suggestions for improvement. I think the manuscript is in excellent shape and can proceed with only minor final corrections. Please see the attached annotated PDF for all comments.

We wish to thank reviewer A for their thoughtful comment and for providing this annotated PDF with additional comments, all of which were very useful. They have now been addressed in the revised version.

**Reviewer B**

After reading the manuscript and the authors’ responses to the first-round reviewer comments, I think the authors have addressed the raised issues and the corresponding revisions made to the manuscript. I have no further comments to add. However, to enhance readability and help readers quickly locate the key study area, it would be nice if the landslide boundary could be clearly plotted and labeled in Figure 1a.

We thank Reviewer B for their positive assessment of the revised manuscript. Regarding the suggestion to add a landslide boundary to Fig 1a, we carefully considered this point. Delineating a precise boundary is challenging, as the geomorphological features highlighted by the digital terrain model (DTM) already indicate the portions of the slope where landslide processes have been most active. Instead, we have clarified in the legend of Figure 1a that “the extent of the DTM shown on the map covers the main area of reported active movement.”

Sincerely yours,

Arnaud Watlet on behalf of co-authors