



<b>Title</b>	Time-Lapse Monitoring of Moisture Induced Landslide Using Surface Waves at Hollin Hill Landslide Observatory
<b>Authors(s)</b>	Wacquier, Loris, Whiteley, J., Gunn, D., Trafford, Andrew, Donohue, Shane, et al.
<b>Publication date</b>	2021-09-01
<b>Publication information</b>	Wacquier, Loris, J. Whiteley, D. Gunn, Andrew Trafford, Shane Donohue, and et al. "Time-Lapse Monitoring of Moisture Induced Landslide Using Surface Waves at Hollin Hill Landslide Observatory." European Association of Geoscientists & Engineers, September 1, 2021. <a href="https://doi.org/10.3997/2214-4609.202120163">https://doi.org/10.3997/2214-4609.202120163</a> .
<b>Conference details</b>	Near Surface Geoscience Conference 2021 (NSG'21): The 27th European Meeting of Environmental and Engineering Geophysics, Bordeaux, France (and Online), 29 August - 2 September 2021
<b>Publisher</b>	European Association of Geoscientists & Engineers
<b>Item record/more information</b>	<a href="http://hdl.handle.net/10197/12753">http://hdl.handle.net/10197/12753</a>
<b>Publisher's version (DOI)</b>	<a href="https://doi.org/10.3997/2214-4609.202120163">10.3997/2214-4609.202120163</a>

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# TIME LAPSE MONITORING OF MOISTURE INDUCED LANDSLIDE USING SURFACE WAVES AT HOLLIN HILL LANDSLIDE OBSERVATORY

## Introduction

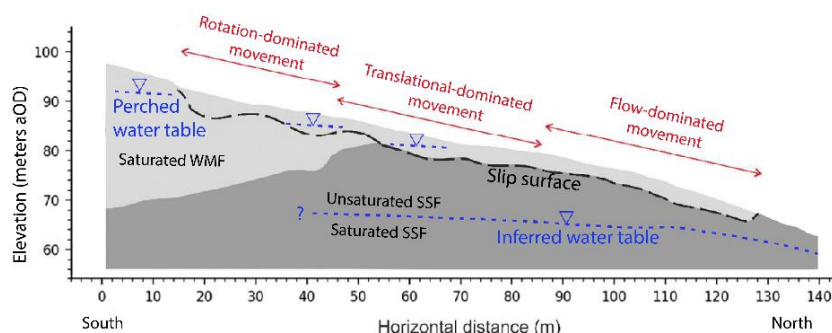
For about fifteen years, the Hollin Hill site has been used as a landslide research site to test different geophysical characterization and monitoring methods, to assess temporal and spatial stability, and the following methods are regularly evaluated on site: ERT resistivity mapping (Chambers et al. 2010, Uhlemann et al. 2017), self-potential methods SP (Chambers et al. 2008), more recently seismic refraction tomography SRT (Whiteley et al. 2020, Uhlemann et al. 2016). The dynamics and ongoing subsurface processes of the Hollin Hill landslide are therefore relatively well described in literature (Whiteley et al. 2019a). Seismic methods based on characterization of P-wave ( $V_p$ ) and S-waves ( $V_s$ ) propagation and in particular on  $V_p/V_s$  ratio are commonly used in a landslide context (Grandjean et al. 2009, Mainsant et al. 2012). Since mid-2000, methodological improvements have led to increased routine use of dispersion inversion of  $V_s$  in hydrological applications (Pasquet et al. 2015; Dangeard et al. 2016) and in geotechnical applications (Donohue et al. 2011, Bergamo et al. 2016). This abstract therefore discusses current geophysical research to monitor seasonal variations using surface waves content (Rayleigh waves) from SRT acquisitions, in the context of moisture induced landslide monitoring, at the Hollin Hill Landslide Observatory.

## Hollin Hill Landslide Observatory (HHLO)

The Hollin Hill site is located in North Yorkshire, England, at an altitude between of 50 and 100 meters. It can be classified as a Moisture Induced Landslide (MIL) (Whiteley et al. 2019b), or a slow-moving earth flow according to Cruden and Varnes (1996) classification. The Hollin Hill site is composed of Jurassic mudstones and sandstones: the lower part of the slope consists of Staithes Sandstone Formation (SSF), while the upper part of the slope, which is actively failing, is comprised of the Whitby Mudstone Formation (WMF), partly overlying the SSF. The main back-scarp is located at the top of the slope in the WMF, with displaced WMF overriding the SSF towards the middle and base of the slope. The degree of saturation on largely controls the amount of displacement (Whiteley et al. 2019a), which is dominated by 3 modes of movement: a rotational-dominated movement mode in the upper part of the WMF, a translational-dominated mode in the middle part of the slope, and finally a flow-dominated mode for the lower part of the landslide (Figure 1).

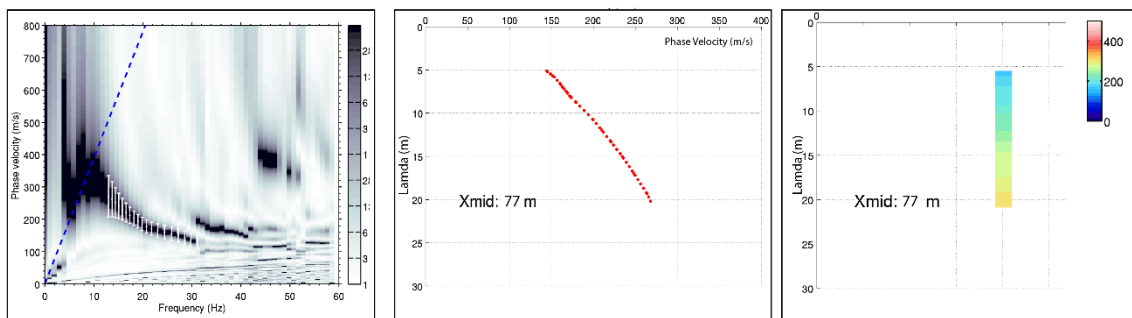
## Analysis of surface waves content using P-wave SRT data.

In this context of monitoring and characterisation of underlying lithological unit proprieties, 16 seismic datasets were acquired between October 2016 and August 2019. The purpose of this study was to identify elastic variations in lithological units, in relation with the seasonal variation of lithological moisture content. In total, 72 vertical component geophones with a maximum dominant frequency of 8Hz were implanted every 2 meters, creating a profile of 142 meters in total, covering the entire landslide. Seismic hammer shots of 4kg were made every two geophones on a horizontal steel plate.



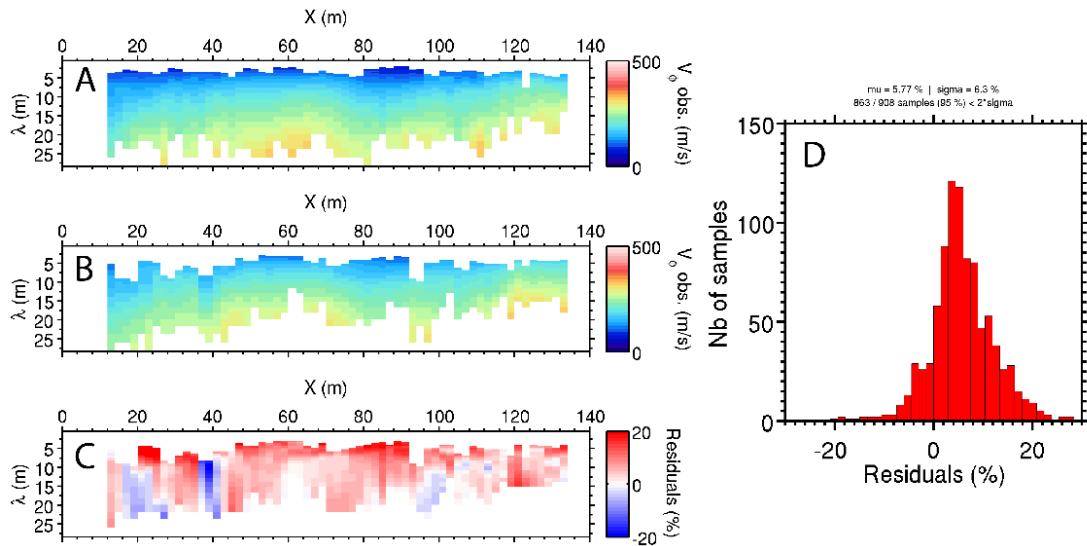
**Figure 1** : Cross-section model of the Hollin Hill Landslide (modified from Whiteley et al., 2020) showing all the geological formations, the movement modes, the slip-surface and an inferred position of the water table. The slip surface displacement is the result of the interface between WMF and SSF and their different characteristics.

In an elastic, heterogeneous and horizontally stratified medium, surface waves are dispersive: the surface waves velocities are directly related to their own propagation frequency. A detailed parametric study was then conducted in order to determine the optimum number of geophone traces to be used for creating dispersion curves, keeping a balance between depth of investigation and lateral resolution. For each 72 geophones dataset, a sliding window of 10 geophones is therefore used to extract the corresponding propagation mode. The 10-geophone window was then shifted downslope, one geophone spacing at a time in order to generate a series of dispersion curves images along the entire length of the profile. The seismic source is located 6 meters upslope of the first geophone, to avoid, on the one hand, near-source effects, and on the other hand confusion related to the propagation modes. For each seismic dataset, 61 dispersion curves images were therefore extracted from the upper part of the landslide to the lower part, and for each sliding window, the dominant fundamental propagation mode was manually picked. For every dataset, the fundamental was relatively well defined between 12Hz and 40Hz. From the 15 seismic datasets (dataset 3 cannot be used), 61 propagation modes were picked when the dispersion mode was well defined (Figure 2A). Each propagation mode picked is then resampled in a phase velocity-wavelength domain (Figure 2B), and then visualized using a colormap (Figure 2C).

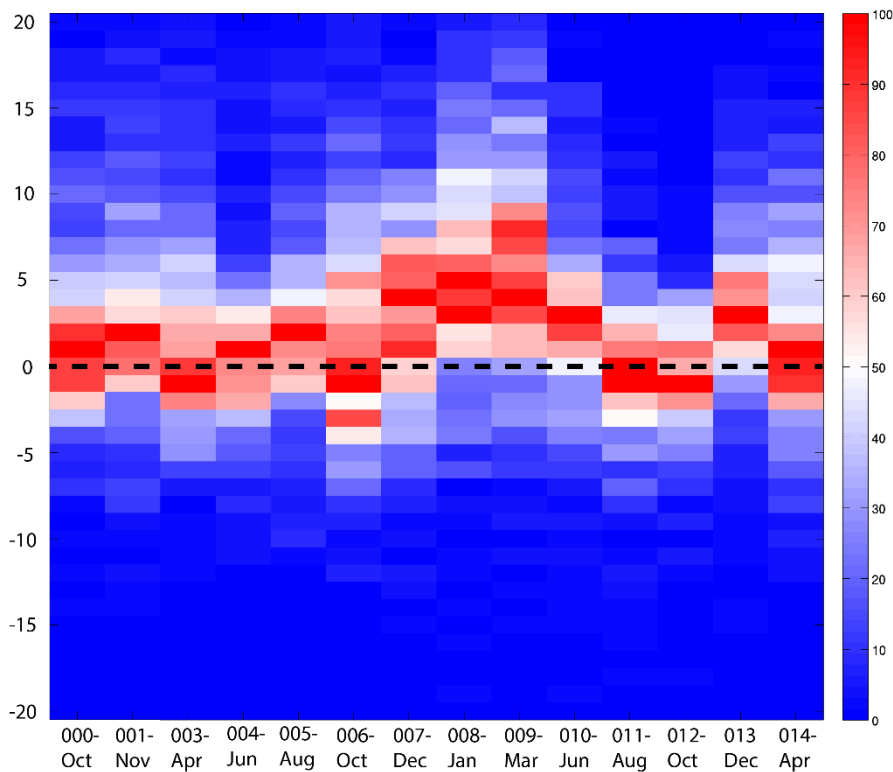


**Figure 2:** A) Dispersion image (frequency-velocity domain) where the fundamental dispersion mode in white is picked from 12Hz to 32Hz. B) Fundamental mode resampled in velocity-wavelength domain. C) Fundamental mode resampled in velocity-wavelength domain visualised with a vertical colormap corresponding to its velocity evolution

Then, each fundamental propagation mode is assembled to form a 2D pseudo section corresponding to the evolution of the fundamental mode throughout the profile (Figure 3A and 3B). All the 2D pseudo sections of propagation modes are consistent and exhibit a similar overall pattern for every dataset. For a fixed wavelength, velocity increases slightly from the top of the slope (0m) to approximately the mid-point of the slope (~70m). The phase velocity then decreases from 70m to 100m, and then increases again from 100m to the end of the profile. Rayleigh waves phase velocity evolution results are qualitatively consistent with S-waves velocity profiles estimated from SRT described in Whiteley et al. 2020. Each 2D pseudo section is then compared to the 2D pseudo section corresponding to July 2019 dataset (Figure 3C). Finally, 14 pseudo sections of residuals were determined, which corresponds to the relative difference between each dataset and the July 2019 dataset (Figure 3C). From each 2D profile of residuals, the statistical distribution of relative difference between a dataset and July 2019 dataset is calculated and represented by a histogram (Figure 3D). Finally, all histograms representing the statistical distribution of each difference with the July 2019 dataset are presented in Figure 4. The high amount of residuals variations (close to a 5% statistical peak of differences) corresponds to the difference between winter and summer (December 2017, January 2017 and February 2017 versus July 2019), and the low amount of residuals variations (close to 0% of statistical differences) corresponds to the difference between Spring/summer and summer (April 2017, June 2017, August 2018 and April 2019 versus July 2019). All these results indicate a seasonal variation control or a soil moisture control on surface waves velocity measurements with time. These results are currently being investigated further and will be discussed in a future work.



**Figure 3:** A) 2D pseudo section of Rayleigh waves phase velocity for the January 2018 dataset, composed of all picked fundamental mode for every sliding window. The left side of the 2D section represents the upper part of the landslide, and the right part of the profile represents the lower part of the landslide. B) 2D pseudo section of July 2019 dataset. C) 2D pseudo section of the residuals, corresponding to the normalised difference in percent between July 2019 and Jan 2018 pseudo sections. D) Statistical distribution of the 2D pseudo section of residuals (Figure C), where the Y axis represents the difference in percent ( $\pm 20\%$ ). Each vertical stick corresponds to the difference between each dataset and July 2019 dataset. Here, the average difference between July 2019 and Jan 2018 is 5.77% (Standard deviation 6.3% and 95% of the samples are below  $2\sigma$ ).



**Figure 4:** All assembled histograms Relative difference between all the 2D pseudo sections profiles and representing the statistical distribution of each difference with July 2019 dataset. The dotted line represents 0% of statistical variation between a dataset and July 2019 dataset.

## Conclusions

Using surface waves, particularly Rayleigh waves characterisation can provide information about the seasonal variations in the elastic properties of underlying lithological units of Hollin Hill landslide system. Specifically, this approach shows potential for monitoring seasonal variability in elastic properties linked to changes in soil moisture, which has a direct impact on periods of more active slope movement. All these links will be further investigated in future work. Another aspect in developing surface waves monitoring is providing a complementary method to SRT-S waves monitoring. However, to allow a direct comparison between Vs estimated from SRT and surface waves propagation, a data inversion step is necessary, which is currently being carried out.

## Acknowledgements

All the surface waves characterisation and the figures have been produced using the open-source Matlab toolbox SWIP (Pasquet et al. 2017). The contributions of the BGS authors are published with the permission of the Executive Director of the British Geological Survey (UKRI).

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