Integrated time-lapse geophysical surveys for hydrogeological characterisation and monitoring of a clay-rich landslide in North Yorkshire, UK

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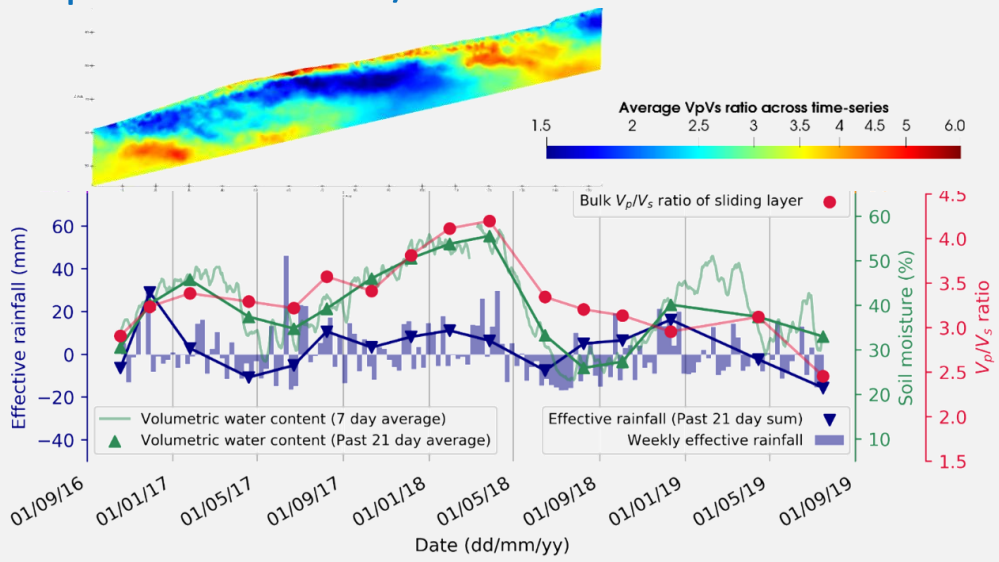
High spatial resolution (HSR) geophysics for landslide monitoring

- HSR methods reveal spatial properties related to shear strength (τf), where c is cohesion, σ is total normal stress, u is pore water pressure, and ϕ'_{cv} is the angle of shear resistance:

$$\tau_f = c + (\sigma - u)\tan\phi'_{cv}$$

Seismic refraction tomography (SRT)

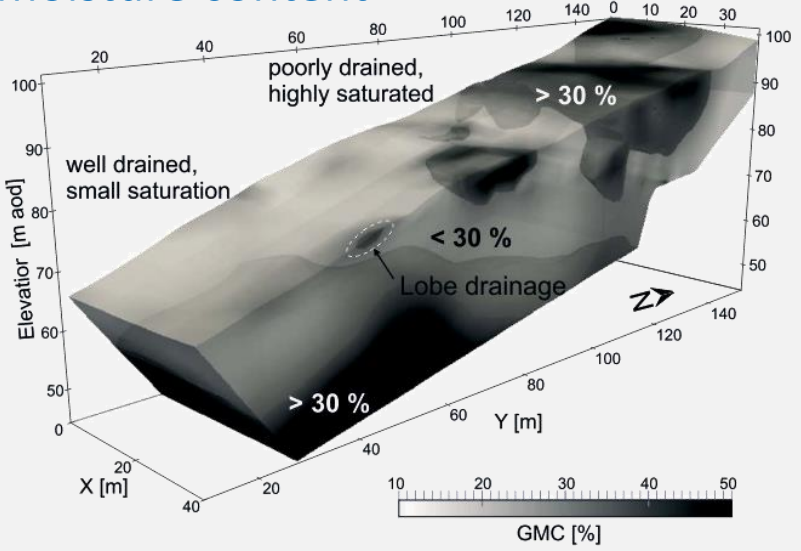
Vp -> saturation / Vs -> stiffness



Whiteley et al., 2020

Electrical resistivity tomography (ERT)

-> moisture content

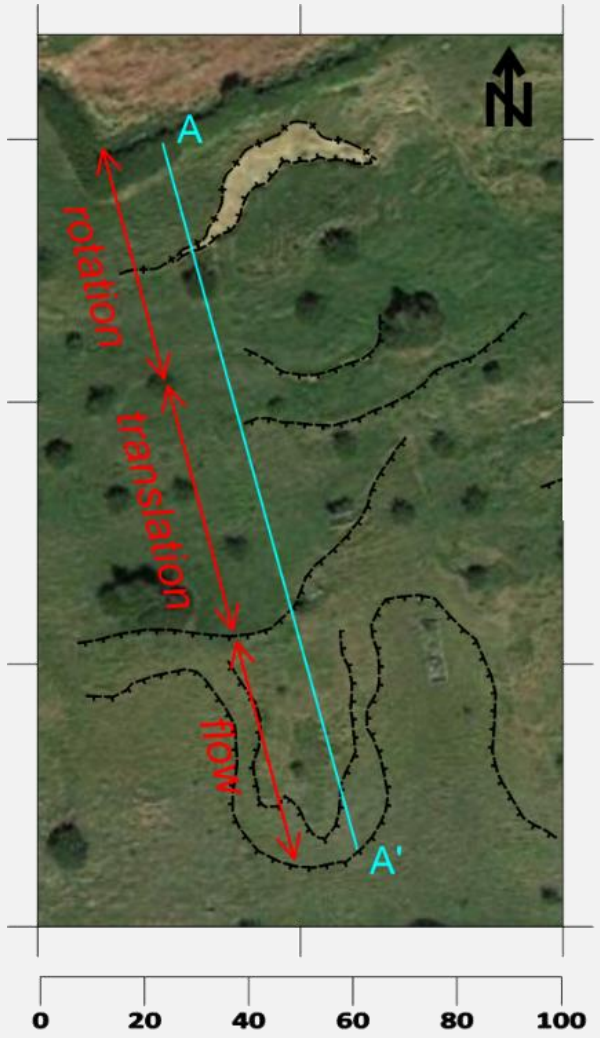


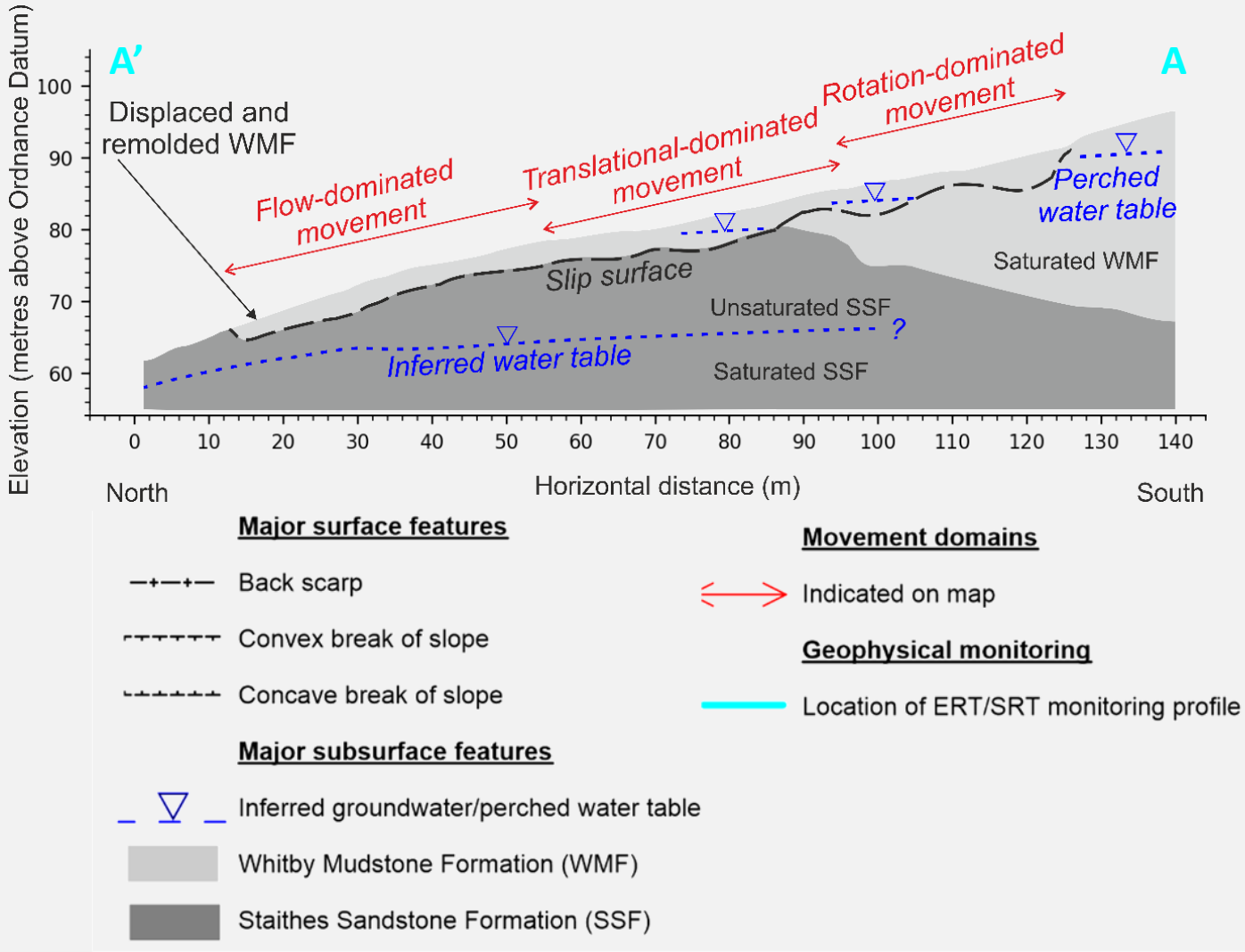
Uhlemann et al., 2017

- Aim: Use HSR geophysics to monitor material variation and improve ground model development

The Hollin Hill Landslide Observatory

- Slow moving (max. 3.5 m per year), stick-slip, complex earth-slide / earth-flow.
- Clay-rich, poorly drained Whitby Mudstone (WMF) fails over free-draining Staithes Sandstone (SSF).





HSR geophysical data acquisition

- 11 ERT surveys acquired from on-site automated ALERT system.
- 11 SRT surveys acquired, both measuring P-wave (Vp) and S-wave (Vs) velocity.
- Both ERT and SRT data acquired at comparable resolution (ERT electrode spacing = 4.5m, SRT geophone spacing = 2m) and close together in time.
- Reliability of comparison between datasets dependent on number of days difference between survey dates.

Time-step	SRT survey date	ERT survey date	Days difference
0	18/10/2016	10/11/2016	-23
1	29/11/2016	01/12/2016	-2
2	25/01/2017	12/01/2017	13
3	19/04/2017	30/03/2017	20
4	22/06/2017	12/06/2017	10
5	08/08/2017	14/08/2017	-6
6	11/10/2017	09/10/2017	2
7	30/01/2018	08/02/2018	-9
8	28/03/2018	15/03/2018	13
9	15/06/2018	14/06/2018	1
10	09/08/2018	02/08/2018	7

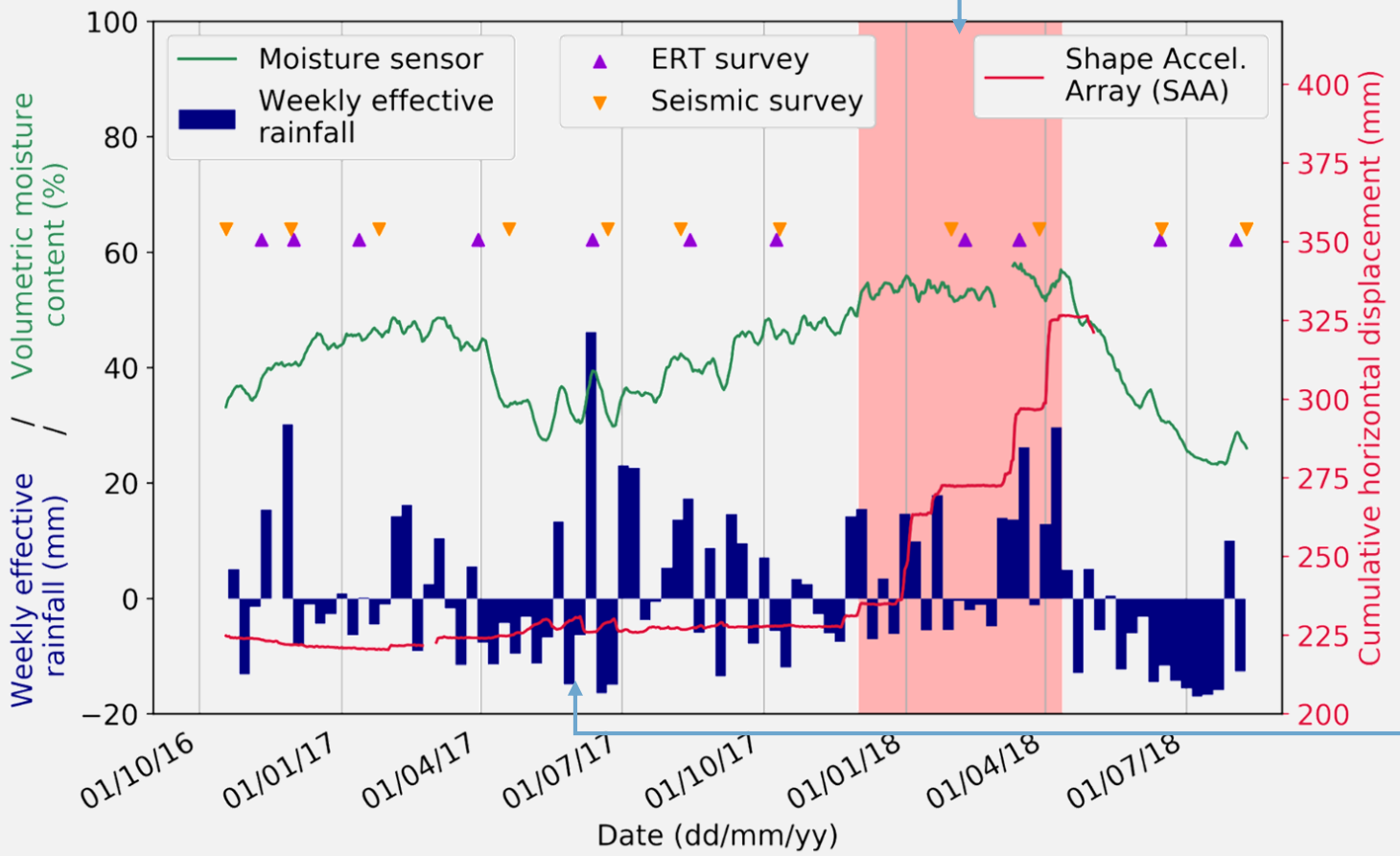
Surveys within 1 week of each other (most reliable)

Surveys within 2 weeks of each other

Surveys more than 2 weeks apart (least reliable)

Movement and geophysical / environmental monitoring

- Rainfall data from on-site weather station, moisture / movement data from wireless sensors.

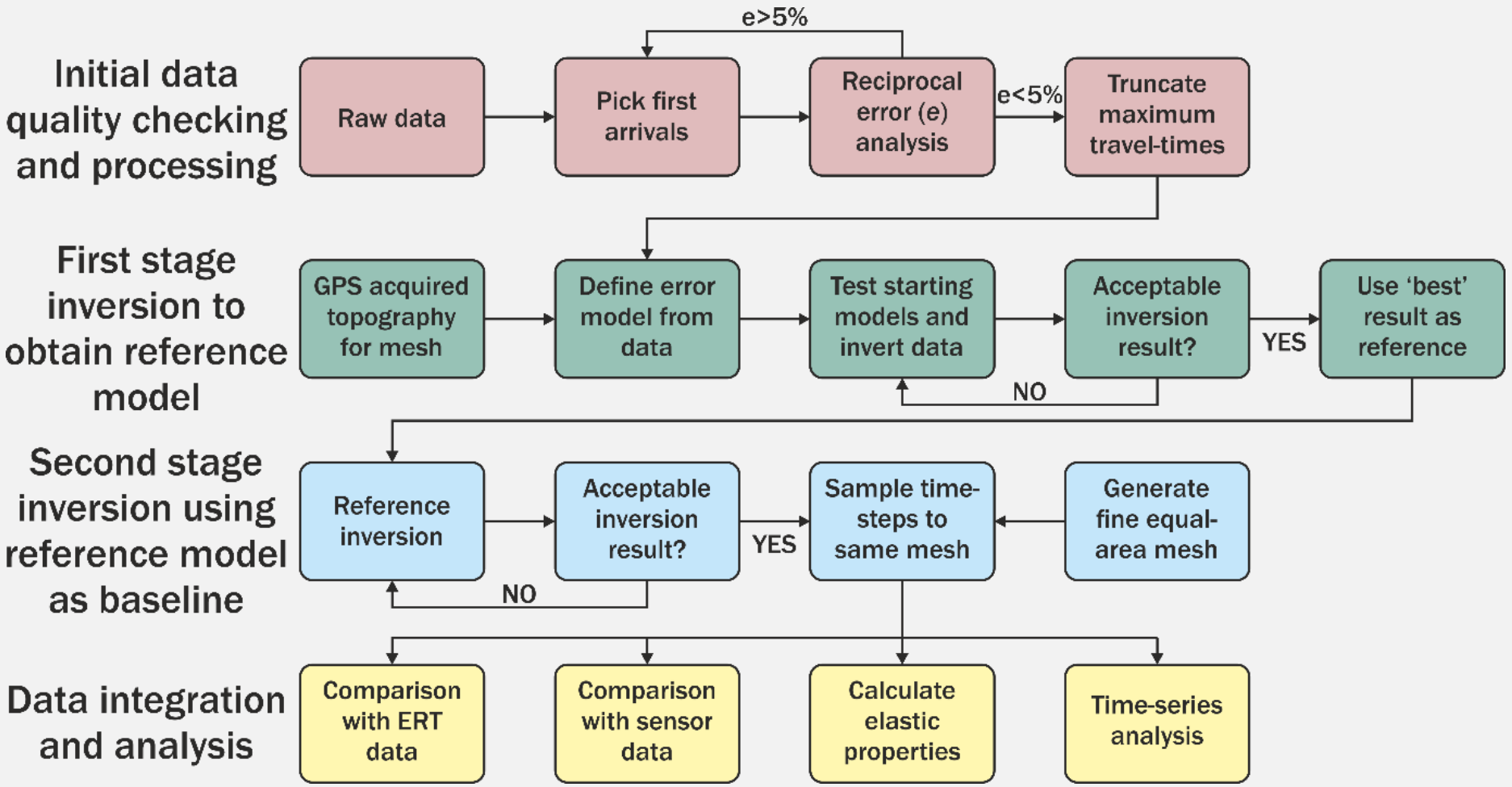


Moderate, sustained effective rainfall with high antecedent moisture (i.e., saturated state) = displacement closely linked to rainfall events (red shaded area)

High effective rainfall, but low antecedent ground moisture = ground expansion / contraction, but no permanent displacement

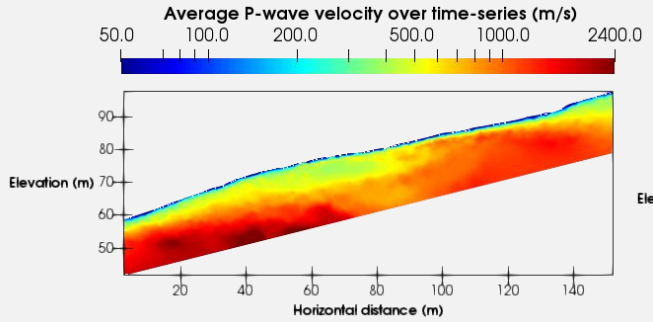
Data processing

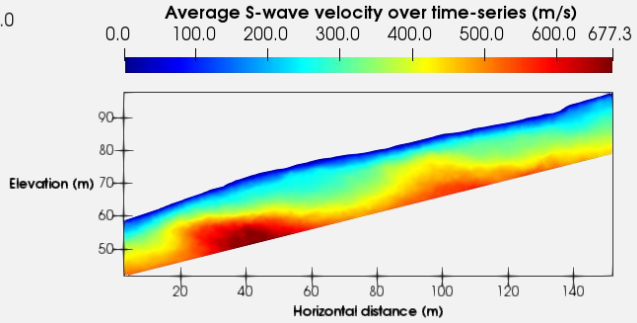
- ERT processed using time-lapse inversion (see Uhlemann et al., 2017).
- SRT processed using ‘reference’ inversion; no SRT time-lapse inversion code (see Whiteley et al., 2020).

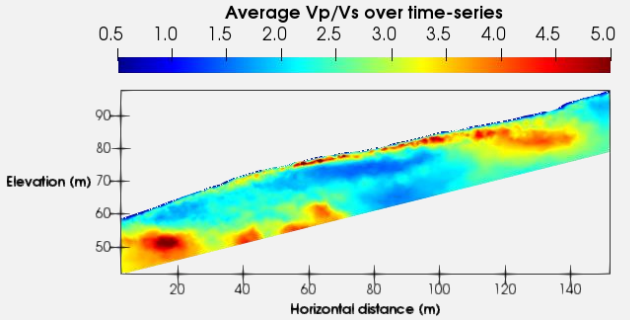


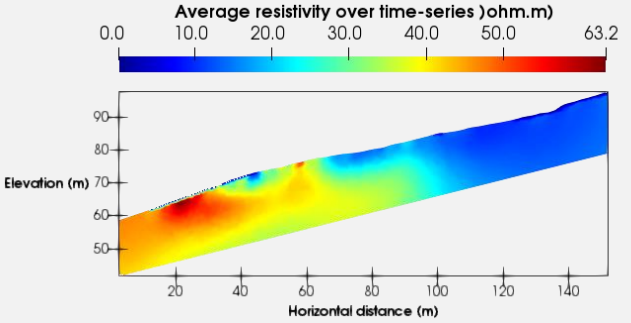
Results

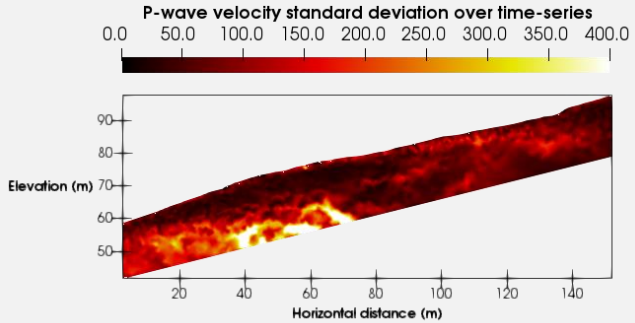
- Average velocity / resistivity sections (top row) show average across the time-series (i.e., 11 surveys).
- Standard deviation plots (bottom row) show the areas of greatest variation across the time-series, indicating the areas of the landslide in which material properties have changed over time.

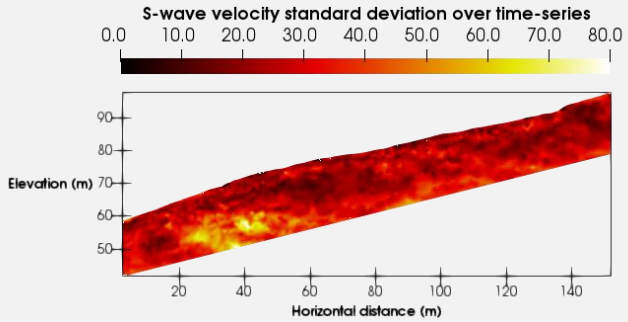


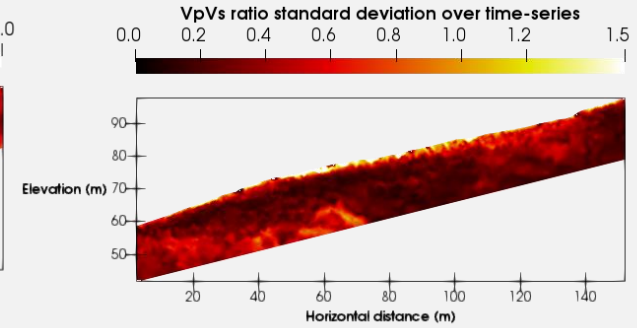


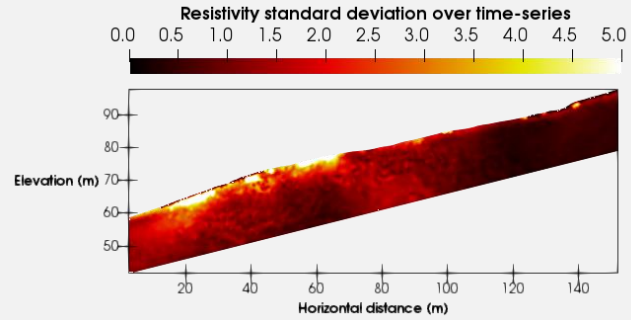






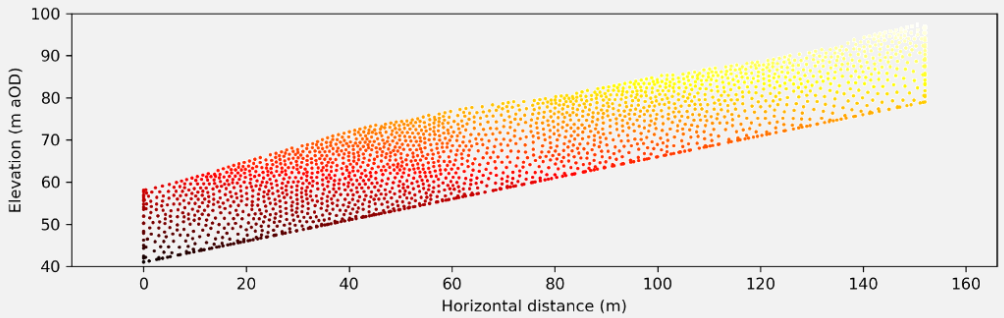




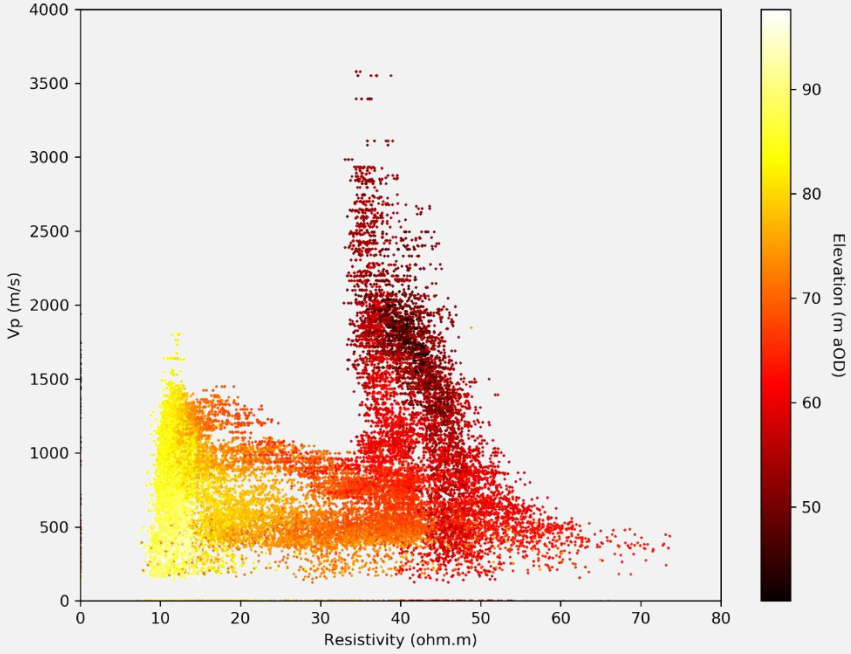


Monitoring processes using HSR methods (1)

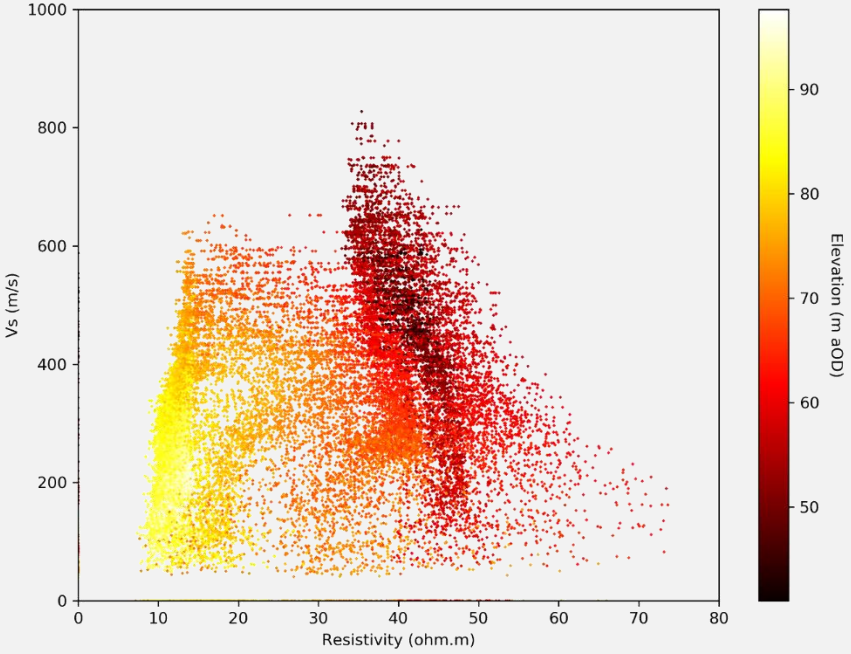
- Data from all surveys sampled to common grid to give subsurface points with values of Vp, Vs and resistivity.
- Cross-plots of point values (of whole time-series) with points coloured with elevation reveals spatial groupings of data.



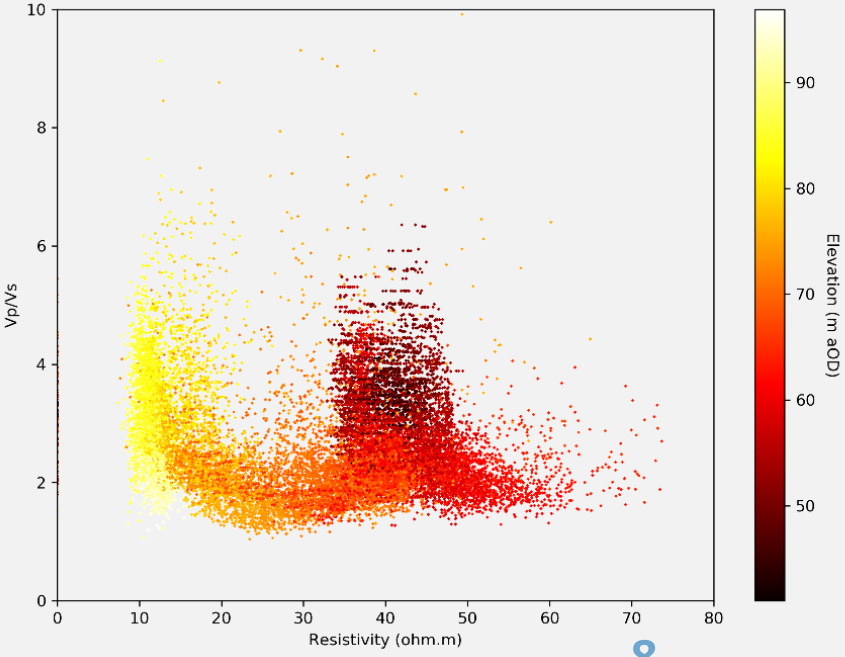
Resistivity vs Vp (whole time-series)



Resistivity vs Vs (whole time-series)



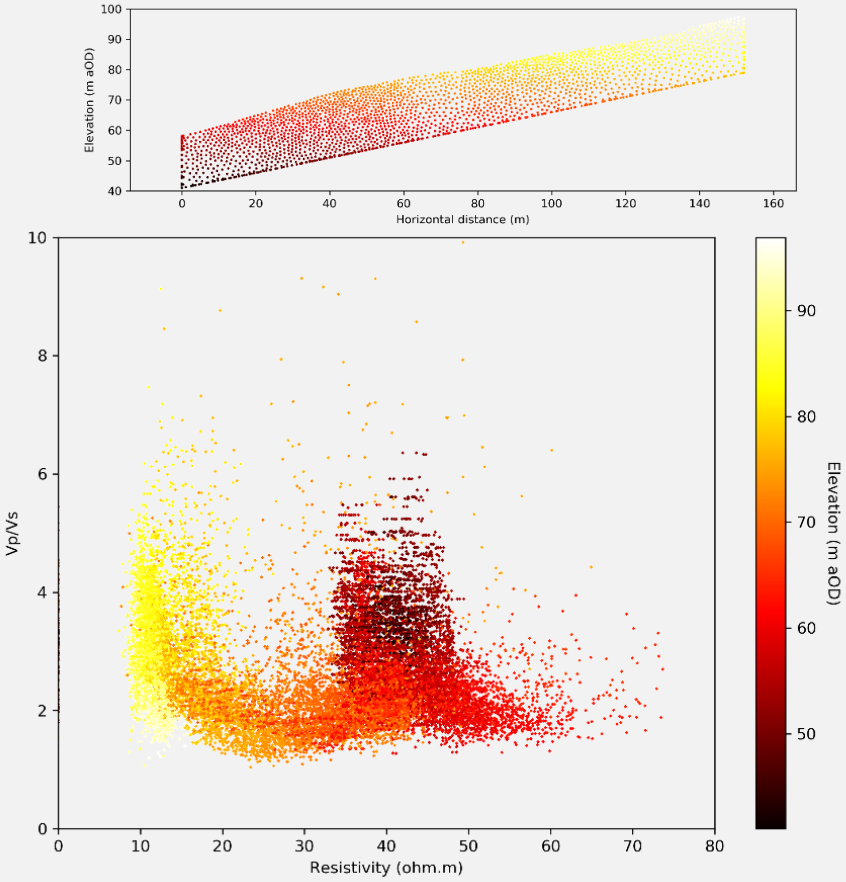
Res. vs Vp / Vs (whole time-series)



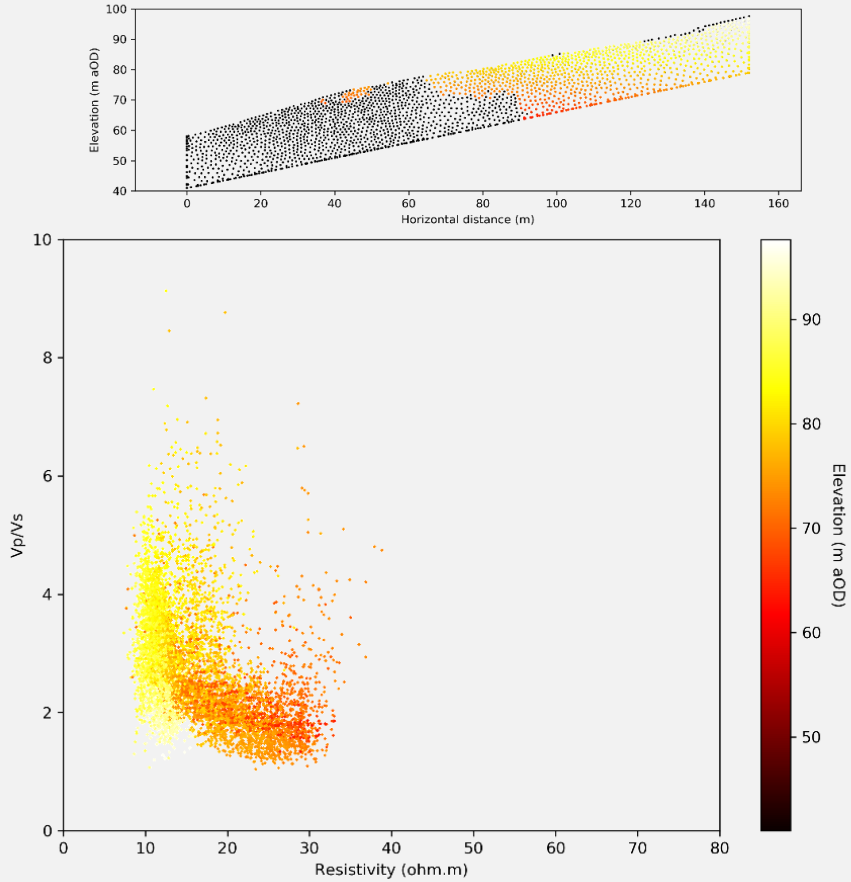
Monitoring processes using HSR methods (2)

- Resistivity threshold (100 ohm.m) used to distinguish between clay-rich WMF and clay-deficient SSF.
- ERT and Vp / Vs ratio show groupings of data; isolating different units shows field relationships.

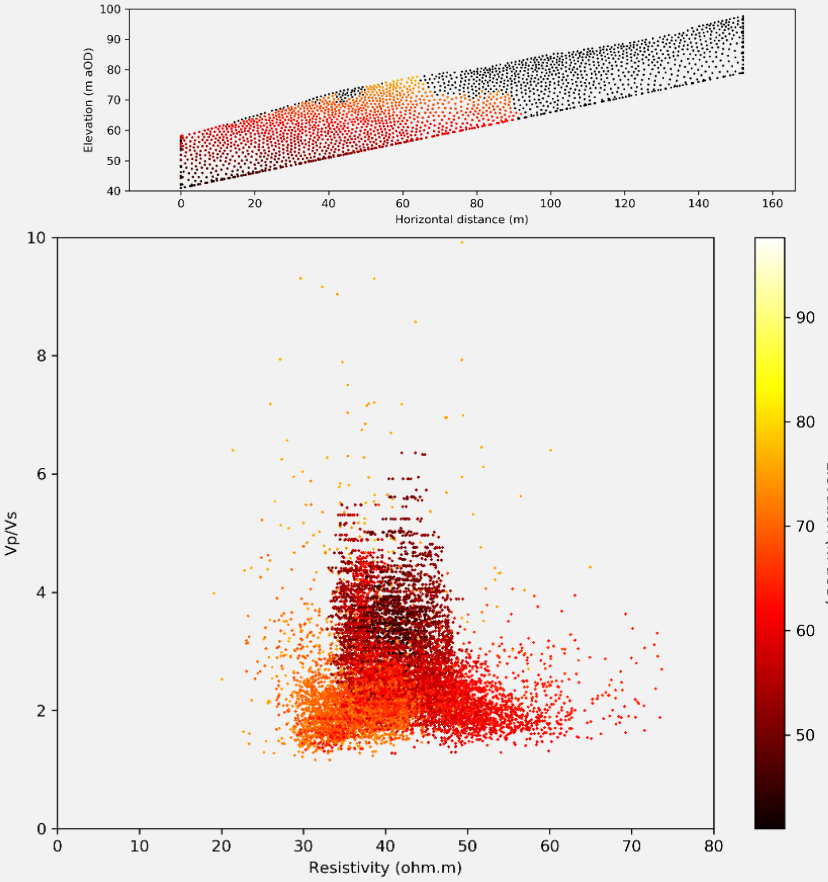
Resistivity and Vp / Vs: All



Resistivity and Vp / Vs: WMF



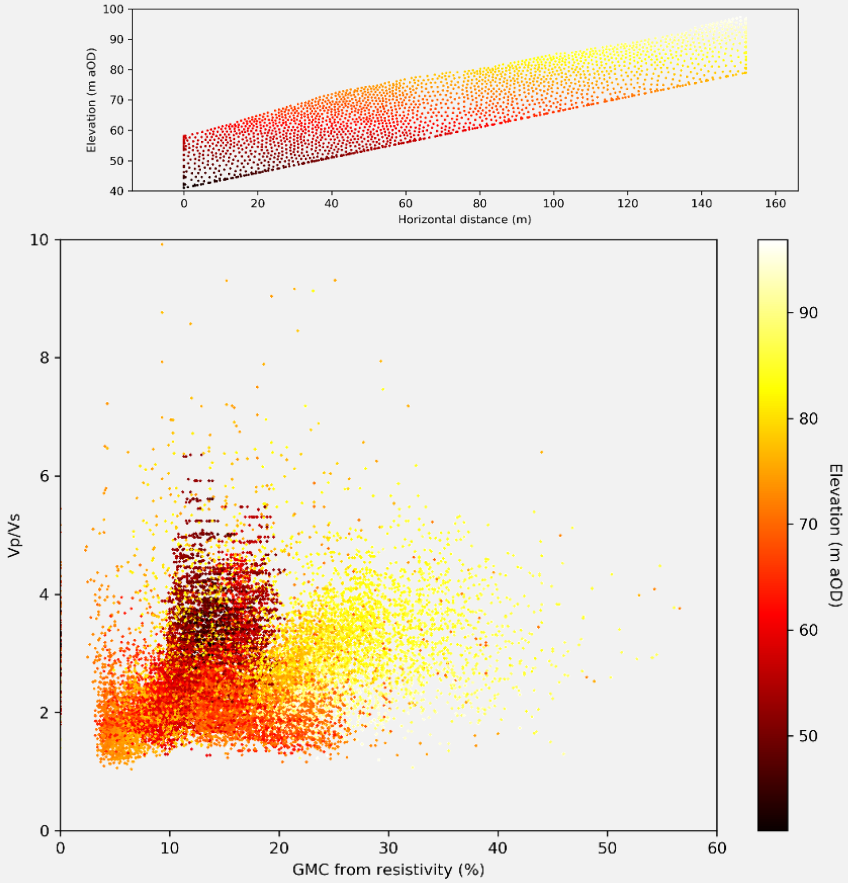
Resistivity and Vp / Vs: SSF



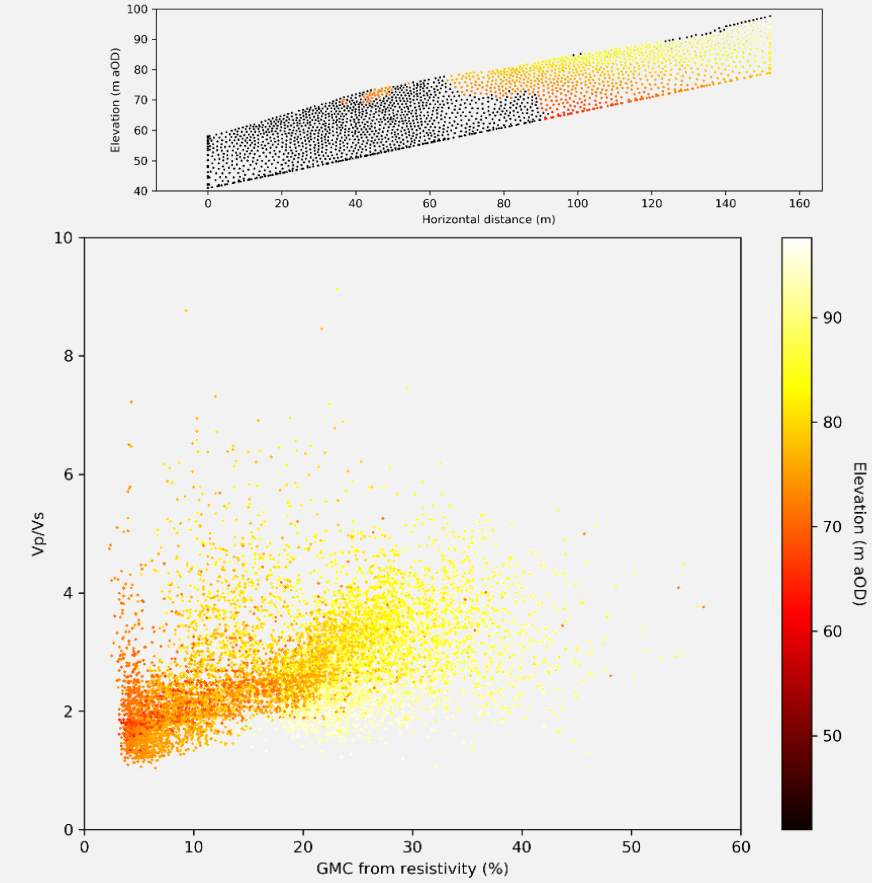
Monitoring processes using HSR methods (3)

- Petrophysical relationship applied to resistivity (Uhlemann et al., 2017) to produce gravitational moisture content (GMC) for comparison with Vp / Vs ratio.

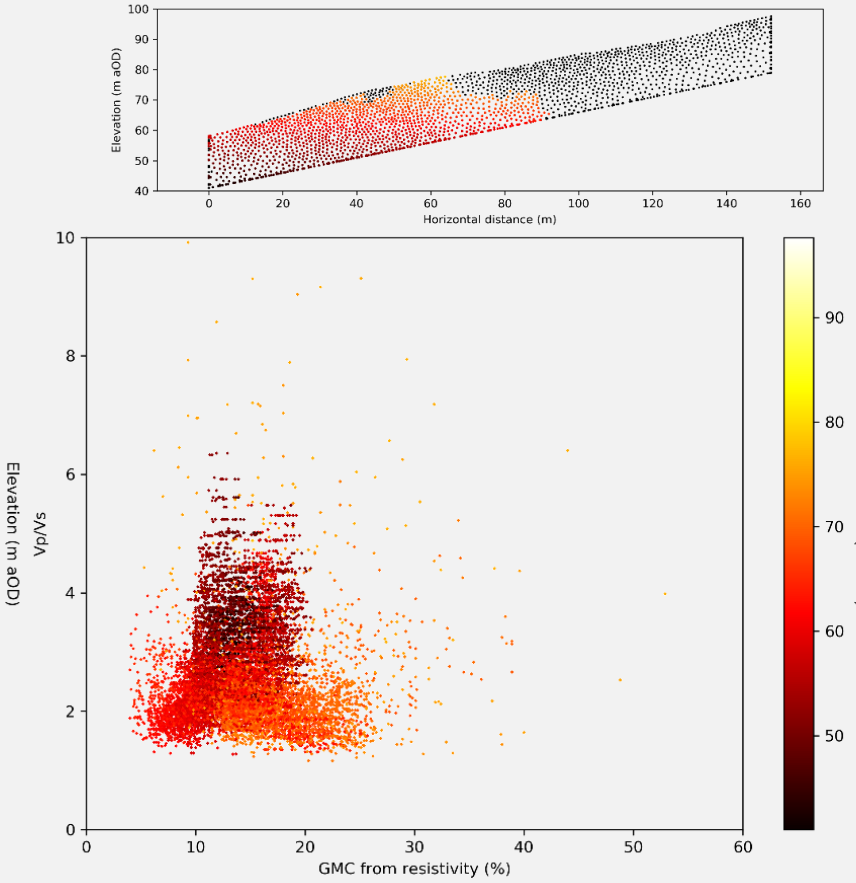
GMC and Vp / Vs: All



GMC and Vp / Vs: WMF



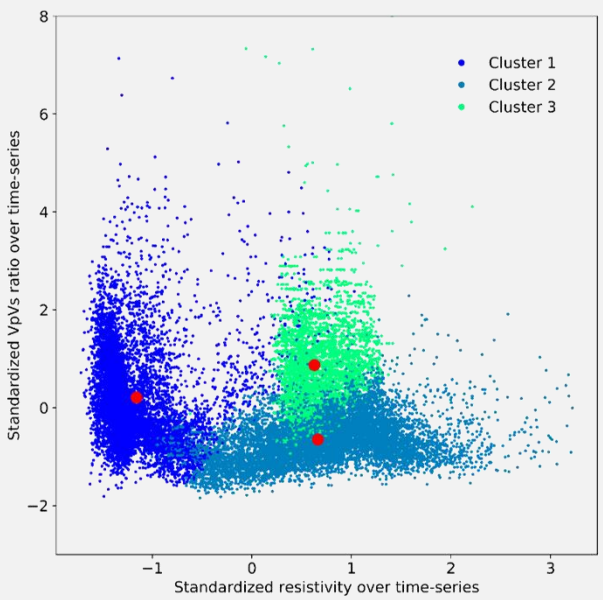
GMC and Vp / Vs: SSF



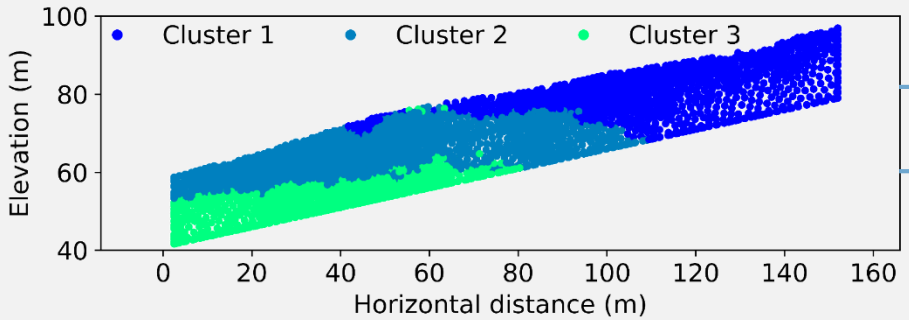
Improving the ground model using integrated surveys

- k-means algorithm to classify geophysical / spatial inputs, rather than use resistivity threshold for lithology.
- Inputs: resistivity, Vp / Vs, elevation and depth of point
- Clustered ground model closer to manually interpreted model

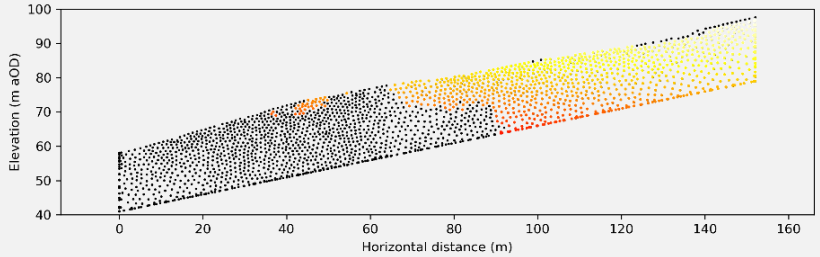
k-means clustering of data



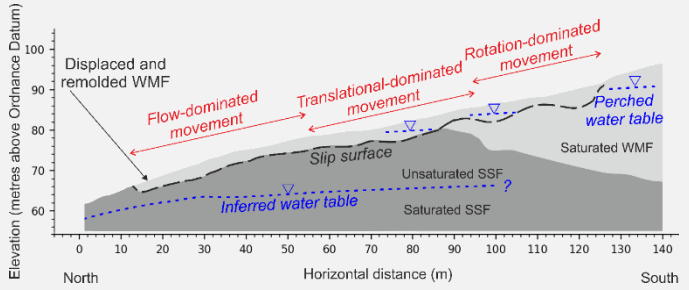
Clustered ground model



Resistivity threshold model



Manually interpreted ground model



Conclusions

- High spatial resolution geophysics, particularly co-located ERT and SRT surveys, provide a useful tool for delineating landslide units based on geophysical properties.
- Time-lapse data from 22 months at the Hollin Hill Landslide Observatory show relationships between co-located geophysical measurements, indicating different units in subsurface.
- Ground models can be improved with the use of automatic classification algorithms, and can be used to improve time-lapse analysis.
- Future work will focus on analysing time-lapse variations within clustered ground model units to assess variations of geophysical properties.

References

- 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.
- 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.