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Innovative monitoring strategies for managing hazardous slopes

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Executive Summary

The aim of the Scottish Roads Research Board (SRRB) Innovative Monitoring Strategies project has been to implement a novel multilevel modular monitoring system to detect landslide activity prior to, during and after landslide events, providing a business case for appropriate monitoring to enable cost-effective management of hazardous slopes in Scotland. Through this research, new monitoring techniques have been developed and deployed at the A83 Glasgow–Argyll road at the “Rest and be Thankful” (RabT); the RabT is perhaps the most challenging site managed by Transport Scotland where steep slopes above the road are susceptible to repeated landslides. Some of the tested technologies are found to be operationally ready and of clear and cost-effective benefit and hence are recommended for immediate implementation, whilst others are likely to yield valuable new monitoring data with further development/research phases prior to becoming operational options.

Of the monitoring techniques explored, it is recommended that the time-lapse photography, on-slope weather gauges and terrestrial laser scanning (TLS) be taken forward for monitoring immediately where known shallow landslide problems or perceived threats exist. The time-lapse imagery is of high temporal resolution, and has been extremely successful in detecting precursory movement on the monitored slopes as well as being able to determine timings for debris-flow events, allowing them to be analysed with respect to trigger mechanisms such as rainfall for the first time. The weather station analyses have proven that on-slope conditions vary significantly from those recorded by nearby SEPA gauges, they are therefore vital for effective hazard mitigation as opposed to generic forecast conditions. The repeat TLS has modelled the slope surface at <0.20 m resolution and has been used to identify, quantify and analyse slope changes; this technology has also successfully detected smaller open-slope failures that were not recorded by other methods.

Other technologies including seismometer arrays, differential GPS (dGPS) and ground-based synthetic aperture radar (GB-SAR) have been tested in the field and show considerable promise. However, these techniques require further development of the data handling and communication elements. This project has collected critical data that can be used to underpin such advances at the RabT, but longer time-series datasets and greater automation is still required for these approaches to be optimised for wider operational deployment. A single seismometer installed on the slope was able to detect drilling noise generated from the roadside, as well as evidence at least one debris flow in October 2018 through data post-processing. A network of four seismometers has now been installed on the RabT and it is envisaged that future work will derive parameters for effective real-time debris-flow detection. The dGPS monitoring stations have been temporarily installed on the slope and data were streamed in real-time back from both the base and rover stations. However higher resolution L2 dGPS units are needed (sub-centimetre accuracy), partially due to the lack of a clear sky view, in order to effectively resolve small precursory slope deformation vital for alerting authorities of imminent on-slope movement. The GB-SAR has been used to monitor the slope during clear, cloudy and rainy conditions with good millimetre level deformation (line of sight) results collected during each test. This technology should in theory be able to provide continuous, millimetre scale data on slope deformation and could be active during storm events, however it remains a high cost option and more testing and processing automation would be required to make this operational.

Whilst the outcomes of this project are directly applicable to Transport Scotland's future management of the RabT, they will also be of potential benefit to other locations on the Transport Scottish network, and those of other road authorities that are susceptible to landslides. The selection of individual techniques, or combination of techniques, for the monitoring of other locations prone to landslides and the frequency of monitoring is likely to be influenced by the geomorphology, potential failure characteristics, and, the likely drivers of failure of the individual slopes.

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1 Introduction

The south-west facing slopes of Beinn Luibhean have long presented a significant landslide hazard to the A83 trunk road that traverses the slope to the Rest and be Thankful (RabT) car park and connects large parts of mid-Argyll with the Central Belt of Scotland.

The A83 leading to the RabT has been subject to a number of closures in recent years due to landslide activity which have necessitated the use of the Old Military Road as a diversion route. These closures have led to the development of significant management and mitigation options at the site which are planned to continue. In particular, significant work has been undertaken to monitor the slope above the A83 at this location (Figure 1; Sparkes et al. 2018 – TRL report PPR 852; Winter et al. 2017 – TRL report PPR 824).

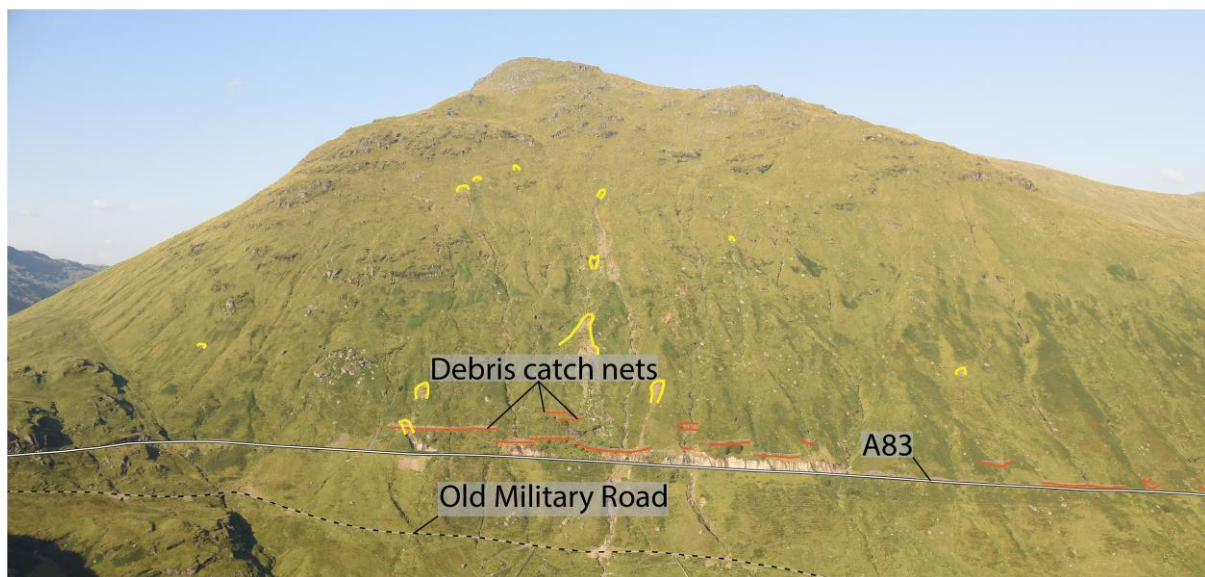


Figure 1 Photo of the slope above the A83 Rest and be Thankful (BNG 223810,707213) showing recent landslide source scars in yellow and debris catch net mitigation works in red.

The work presented in this report describes the application of novel and innovative techniques to support monitoring of the slope above the A83 and complements the work reported by Winter and Ferreira (2019 – TRL Report PPR 908) to capture time-series panoramic imagery.

The aim of the Innovative Monitoring Strategies project has been to implement a novel multilevel modular monitoring system to detect landslide activity prior to, during and after landslide events, providing a business case for appropriate monitoring to enable cost-effective management of hazardous slopes in Scotland. It also allows a benchmark set of data to be established prior to potential reforestation of the slopes above the RabT.

This report details the achievements that have been made against the stated grant objectives (Section 2), shows the equipment installations at the RabT and provides example data (Section 3), evaluates the pros and cons of each approach (Section 4), and gives firm, summarised recommendations about each technology that has been utilised (Section 5). Data

are currently archived at Newcastle University / Northumbria University on behalf of Transport Scotland, to whom any enquiries should be directed.

From 2017 to 2019 project equipment and time has been kindly funded by the Scottish Roads Research Board. From August 2017-2019 a Newcastle University funded Post-Doctoral Research Associate also worked on equipment installations and data processing. Time-lapse camera equipment originally purchased by SRRB was subsequently repaired/replaced using Newcastle University funds. Additional 'event response' terrestrial laser scans of the site during October 2018 were also conducted outside of the project scope using university funds and are therefore retained at Newcastle and Northumbria Universities. During the project, negotiations commenced between Transport Scotland and the landowner regarding the sale of the land. Limitations were imposed on access to the site during these negotiations, as described in the text.

Abbreviations

DEM – Digital elevation model

dGPS – Differential global positioning system

dSLR – digital single lens reflex

GB-SAR – Ground-based synthetic aperture radar

NIR – Near infra-red

NTRIP – Networked Transport of RTCM via Internet Protocol

OSGB – Ordnance Survey Great Britain

RabT – Rest and be Thankful

ROI – Region of interest

SEPA – Scottish Environment Protection Agency

SRRB – Scottish Roads Research Board

TLS – Terrestrial laser scanning

2 Achievements against stated objectives

The following section will set out the objectives stated in the SRRB Innovative monitoring strategies for managing hazardous slopes project proposal and then show what outcomes have been achieved against those objectives.

Objective 1: Epoch based surveys, supplemented with ‘event’ based responsive surveys

Epoch based, terrestrial laser scanning (TLS) surveys and photography aim to quantify changes on the slope between each survey. TLS provides a centimetre scale method of developing digital elevation models (DEMs) which can quantify 3D failure volumes or areas of instability. Photographs of regions of interest (ROI) help to identify specific pre- and post-failure conditions for analysis.

1. *Change detection maps in OSGB; Digital Elevation Models*

Change detection maps between epoch-based TLS surveys have been produced in OSGB format along with high-resolution DEMs of each TLS survey. Cumulative loss and gain maps of the RabT slope from March 2015 to November 2019 are available as well as individual GIS shapefiles and depth rasters of failure scars and depositional areas.

2. *Imagery for Regions of Interest (ROI) and vector plots of feature tracking*

Imagery for Regions of Interest (ROI) has been collected by time-lapse camera installations, ROIs have been utilised to generate feature tracking vector plots of deforming areas of slope which signal precursory movement before failure. Monoplots (georeferenced imagery on DEMs) of imagery have also been explored, however their usefulness has been superseded by vector tracking software.

Epoch based Ground-Based Synthetic Aperture Radar (GB-SAR) surveys, which can monitor the deformation of large-volume targets such as slopes, were carried out over three days in differing weather conditions (clear, cloudy and rainy). The instrument collected good quality data across all environmental conditions, and this points to the possibility that mm scale deformation could be detected if a permanent installation was used. However, there was no natural slope movement detected during the GB-SAR monitoring period, just ongoing works by Geo-Rope, therefore the ability to detect small-scale deformations could not be confirmed. Ideally the GB-SAR needs to be deployed during a storm event and be used to detect precursory movement. The preliminary results from the data and complex processing workflows will be reported separately in the journal Remote Sensing of Environment (Wang et al., In Press).

Objective 2: Continuous monitoring

Continuous monitoring is useful for analysing in detail the slope conditions that have led up to an event occurring. This includes the analysis of high-resolution weather data (rainfall, wind) to look at antecedent conditions, tracking of single point differential GPS (dGPS) and tilt

meters data, monitoring the slope with time-lapse imagery and the use of seismics to detect and triangulate 'noise' sources, such as debris flows, on the slope.

1. Navstar Infrastructure, dGPS and weather station - GPS vectors of motion; on-slope rainfall for comparison to lower stations; long-term testing of Navstar infrastructure for real-time data provision

Two Navstar dGPS monitoring stations (Base and Rover stations) were installed in May 2016, to monitor an area of the slope that was thought to be creeping, however due to the high annual costs and 3rd party data portal it fell out of use in 2018 and was not maintained further. dGPS monitoring was continued using lower cost Emlid Reach units. Real-time data streaming and processing was achieved using these units, and this workflow will be taken forward using new L2 dGPS units that can record sub-cm motions through time. Whilst the Reach units were placed on areas that were expected to move, there was no motion over the monitoring period; nonetheless they remain a targeted monitoring solution capable of 24/7 data in ROIs at a low cost per sensor, they are also well suited to long-term monitoring of individual boulders identified as posing a hazard.

The Navstar weather station was replaced with a near real-time streaming Davis weather station placed centrally on the slope. The unit is continuously logging but sends data every 5 minutes. A comparison of the on-slope gauge to the nearby SEPA Loch Restil gauge shows that on-slope conditions can be significantly different to those up valley (Table 1).

Table 1 Forecast rainfall data from the Met Office and corresponding daily cumulative rainfall totals (millimetres) from the on-slope gauge run by Newcastle/Northumbria Universities, and the nearby Vaisala and SEPA gauges

Date October 2018	Forecast (mm)	Vaisala gauge (mm)	University gauge (mm)	SEPA gauge** (mm)
Sun 7 th	15 - 20*	28.6	57.2	64.8
Mon 8 th	25 - 30	27.0	56.8	86.6
Tues 9 th	42	37.1	86.6	30.0
Wed 10 th	0	0	0	0
Thurs 11 th	5 - 10	6.0	15.4	39.0
Fri 12 th	8 - 12	15.8	40.0	12.0
Sat 13 th	15 - 20	14.6	21.2	19.4

*forecast is from Friday 5th October 2018

**cumulative rainfall is from 9am to 9am, not 12am to 12am

Tilt meters were installed on sections of the slope that had had historic movement and were identified as a likely area for further deformation. However, the tilt meter data did not reveal

any insight in to slope processes as they were easily disturbed in the upper soil profile by weather, frost heave and vegetation. No further analysis of tilt meter data will be conducted in this report.

2. *Seismic Monitoring* - *Assessment of the use of industry standard and low-cost novel seismics to detect and locate events in real time for warning purposes; assessment of event magnitude assessment from seismic data when compared to volumetrics of events.*

Restrictions on installation during negotiations for the intended land sale means that installation of this equipment could only be completed in September 2019 towards the end of the project. However, in a location with prior permissions but poorly suited to seismics, a low-cost, novel, Raspberry Shake 3D seismometer was installed in summer 2018 and was active during the October 2018 landslide event. Post-processed data was able to resolve one of the debris-flows from 9th October 2018 including direction to the sensor. With the land-sale now completed we have installed four Raspberry Shake 3D seismometers on the slope for improved landslide detection and location. Real-time data capabilities have been tested and are functional when stable communications are available. Alarm settings for event detection need to be threshold driven from data collected during future landslide events.

A set of Guralp 6D seismometers were loaned from the NERC Geophysical Equipment Facility in 2017; however due to restrictions on equipment installation because of the land sale these were not installed and had to be returned in spring 2019. Therefore, an assessment of the low-cost sensors to the industry standard seismometers has not been possible.

3. *Time-lapse digital single lens reflex (dSLR) camera and lower resolution sensors* - *Assessment of ability of time-lapse systems to track ongoing deformation, and, provide timing of on-slope failures relative to drivers of failure; time-lapse videos*

Two Harbortronics time-lapse cameras have been installed at the site, one on-slope monitoring areas of interest and one across the valley with a wide-angled view of the entire slope. The cross-valley installation has a full-frame dSLR giving high-resolution imagery of the slope. This imagery has been used to detect precursory slope deformation before failure as well as to corroborate open-slope failures detected by the TLS surveys. Deformation tracking using sequential images has been conducted manually, however it is anticipated that future monitoring will use automated tracking algorithms.

Two Little Acorn 6210MG trail-cameras have also been installed on the opposite valley-side to the RabT. These low-cost cameras send low-resolution (2MP) images back to a designated email account every 15 minutes and can be used for near real-time monitoring of the slope during weather events and for time-sequencing of landslide events after landslides. Landslide timings are important for integration with other data, such as rainfall, to determine thresholds for landslide initiation.

4. Low-cost dGPS monitoring stations - *Continuous record of deformation of ROI; assessment of the reliability of dGPS point based measurements of on-slope activity as compared to photogrammetric.*

Two Emlid Reach L1 dGPS units were installed on the slope as a base and rover respectively. The rover was placed on an area that deformed during the 9th October 2018 landslide events but did not fail. However, it did not move further during the dGPS monitoring period. Data from the L1 rover unit show that they are not of high enough resolution at all times due to poor sky view / satellite geometry to resolve cm scale ground deformation; the point scatter for the majority of the data was up to 0.2 m up and down slope from the actual sensor location.

Improvements can be made to this setup either through temporal filtering, or, preferably by using L2 dGPS sensors able to resolve cm scale deformation and by placing the base station in a location with better sky view to allow for improved real-time corrections.

3 Innovative monitoring: Equipment installations and data outputs

3.1 dSLR Time-lapse camera

A long-term solar charged Harbortronics time-lapse camera installation with a Nikon D800 full-frame dSLR camera was been installed at the RabT for the monitoring period. This allows slope-wide photography every 30 minutes during clear conditions (Figure 2).



Figure 2 A) The dSLR installation and a co-located trail-camera; B) Photo from the dSLR installation

Over the monitoring period the time-lapse imagery from this camera has been used to pinpoint the times for landslide occurrence, both those that have impacted nets at the road and open slope failures which have not reached the road. Camera images were also used to detect precursory movement of material before failure in October 2018 and a report sent to stakeholders (Figure 3).

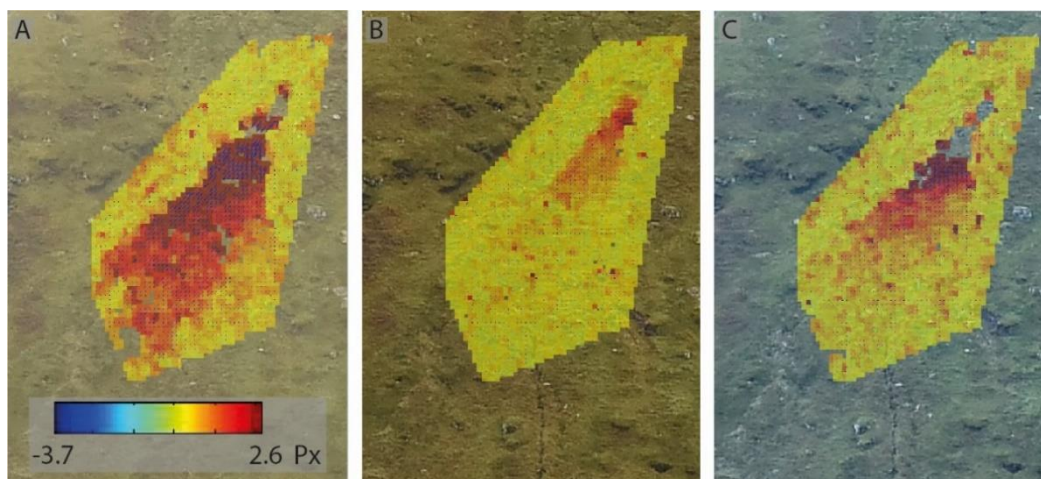


Figure 3 Example deformation tracking from sequential time-lapse images showing higher (dark red) and lower (yellow) rates of movement, in pixels, between images

Precursory movement was detected in retrospect on another open slope failure in August 2019. Software can automatically track this deformation from successive images; however it

has only been possible to do this retrospectively as camera images need to be downloaded manually. Future upgrades to the dSLR should include near real-time data streaming and automatic image tracking. Deformation tracking between images has clear potential for use as a warning to authorities that material on the slope is moving and that there may be increased risk.

3.2 Trail camera time-lapse

Little Acorn 6210MG trail cameras taking repeat photography of the slope every 15 minutes; 5MP images are taken and stored on unit and 2MP images are sent for remote rapid analysis. Colour images are taken during the day and near-infrared (NIR) images taken at dawn and dusk extending the effective monitoring capacity. Colour images have been used to sequence landslide timings, specifically those in October 2018 (Figure 4).

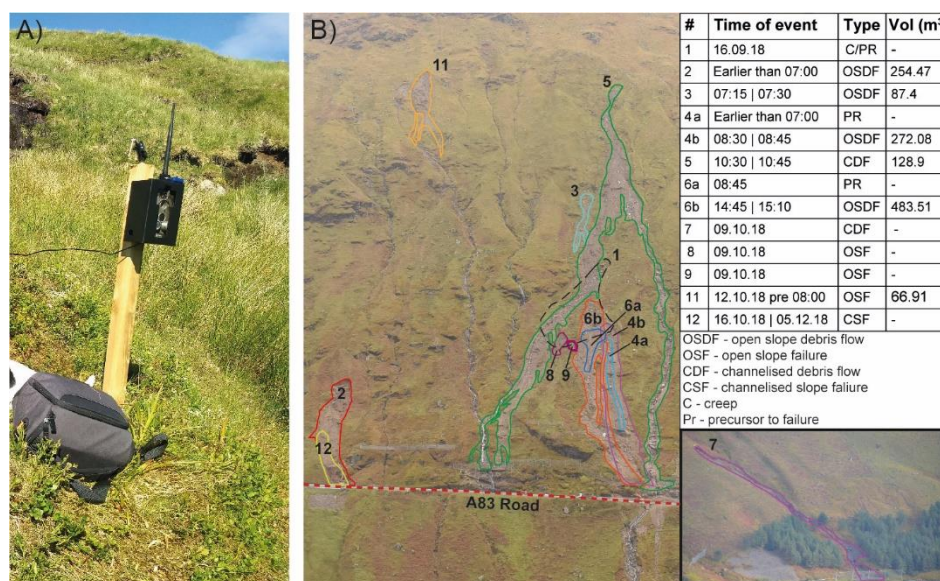


Figure 4 A) Trail camera installation at the RabT; B) 9th October 2018 landslide sequencing derived from time-lapse camera and trail camera data. Some landslides could be narrowed to a 15-minute period

NIR images that are taken at dawn and dusk have shown that it is possible to extract information on landslide occurrence by processing these images and subtracting sequential images from each other (Figure 5).

Currently this NIR subtraction technique requires manual inputs, however progress has recently been made in automating the process. Full automation requires further research and development. The trail cameras serve a similar purpose to the dSLR camera but are significantly cheaper and easy to install. At ~0.5mb per image, the data transmission requirements are also much lower than those of the dSLR allowing for greater temporal resolution of the data. Unfortunately, the low resolution of the images means that only large events can be detected and no detection of precursory deformation is possible.

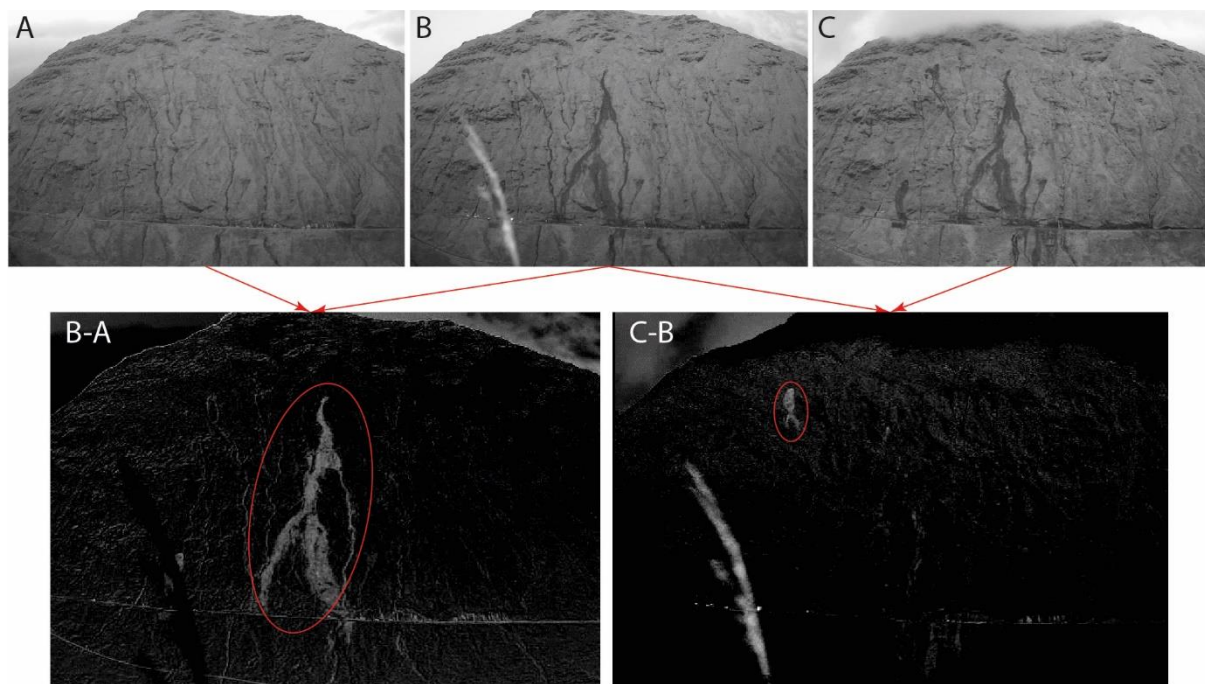


Figure 5 Example of the Near Infra-Red (NIR) image subtraction technique used on the trail-camera imagery to detect debris-flows that reached the road and smaller open slope-failures which did not reach the road

3.3 Davis weather station (Vantage Pro2)

The on-slope weather station logs data directly and provides near real-time (5 min) data transmission to an online viewable data portal (Figure 6). Data include rainfall, rain rate, temperature, wind speed and wind direction. The weather station streams the data back to a portal where it can be accessed by stakeholders.

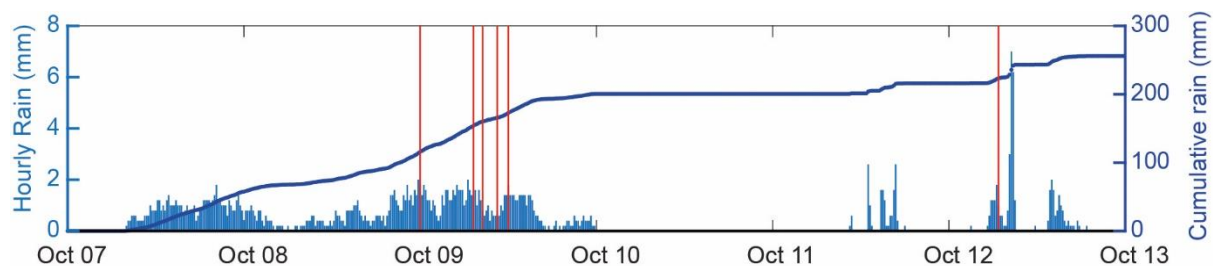


Figure 6 Continuous rainfall data for the period 7th October to 13th October 2018. Hourly and cumulative rainfall over the period are shown along with the timings of events (red lines) as detected on the time-lapse camera imagery

Using the timings of landslide events from the cameras, the data from the weather station can be used to examine the rainfall thresholds (duration-intensities) required to trigger landslide activity on the slope (Winter et al., (2019).

3.4 Seismometers

Four Raspberry Shake 3D seismometers are currently installed on the RabT (Figure 7) close to areas which may be expected to produce landslides. They log data to the unit but can be

configured to stream data in real-time - this configuration is ready to be deployed when stable communications are available.



Figure 7 An example of one of the Raspberry Shake seismometer installations. The units are housed within an IP67 waterproof box with a separate battery box adjacent to the installation

Seismometer data can be displayed and used in a number of ways. The basic trace (Figure 8A) shows the digitised signal from the 3-axis geophones on the seismometer unit; alarms can be set whereby if a threshold of 'noise' is reached then alerts can be sent to key stakeholders. These alarms are usually based on a ratio of the short-term to long-term average of the trace and if that ratio is exceeded by a large event.

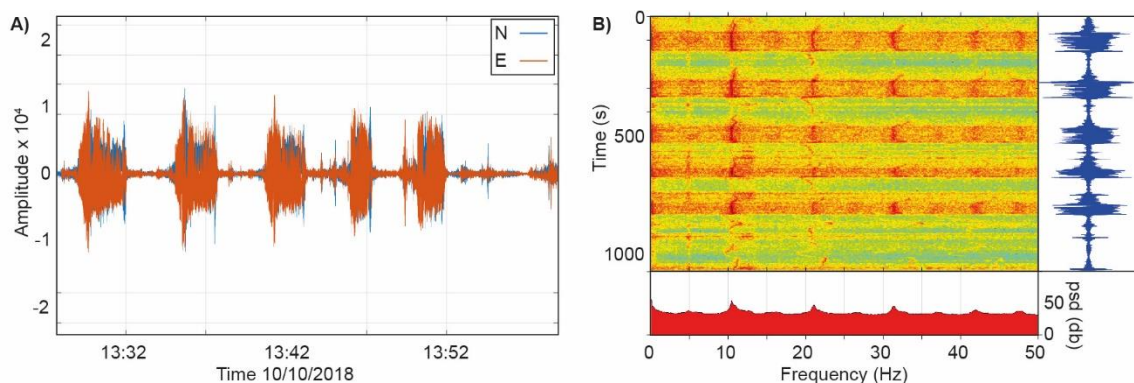


Figure 8 Example seismometer data from October 2018. These data show a 20 minute section of data where man-made drilling noise was occurring on the road side. A) East and North axis, filtered, geophone traces showing the 'noise' of periodic drilling in the A83 catch-pits. B) Peaks in the frequencies of the same dataset, diagnostic frequencies of debris flows and be used to identify them in the seismic signal.

Figure 8B shows the spectrogram of the same section of data as Figure 8A. However, here the frequencies of the 'noise' being detected by the seismometers can be examined. The principal noise detected was man-made, comprising drilling for the construction of catch-pits at the side of the A83. Peaks in frequencies can be seen at ~10Hz, 20Hz and 30 Hz. Landslides and debris flows also have characteristic traces and frequency descriptors that can potentially be thresholded using the seismometers installed on the slope to automatically detect and locate events in real-time.

3.5 dGPS monitoring stations

A dGPS base and real-time deformation tracking rover were temporarily installed on the site. The base was securely located in an area which was not moving and the rover was placed in an area that had moved during the October 2018 landslide events, but had not transitioned into a long-runout failure. Real time streamed and processed corrected positions can be obtained and plotted from the Emlid dGPS units and an NTRIP server process (Figure 9).

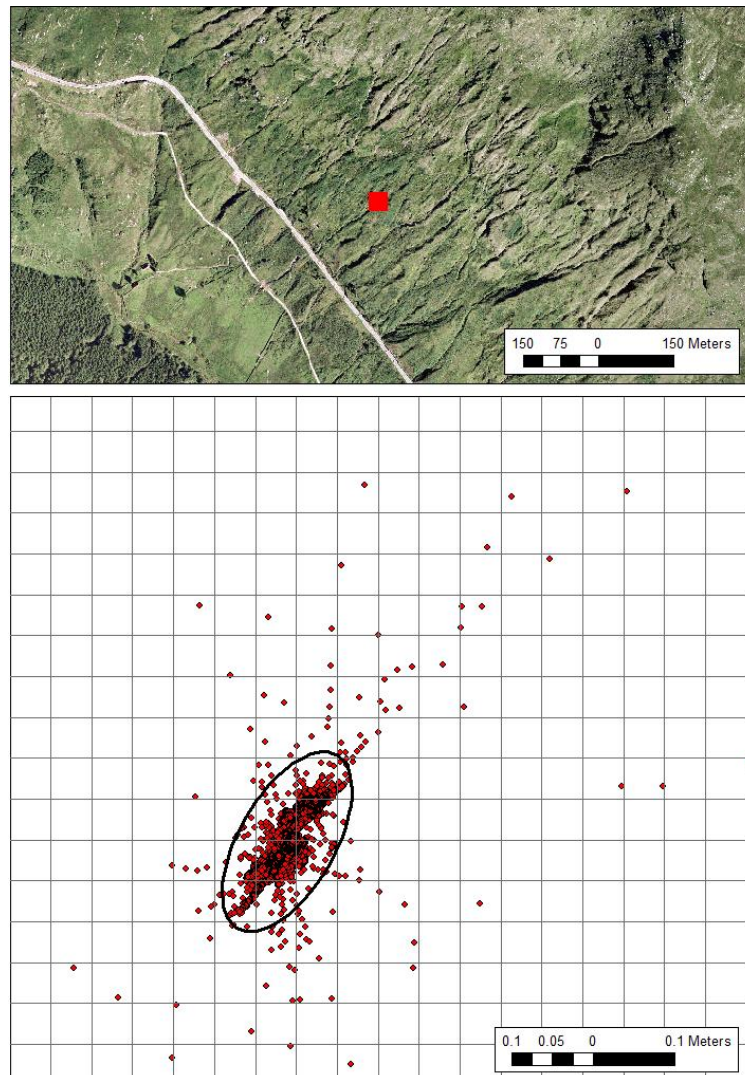


Figure 9 Location of dGPS testing (upper), and, (lower) all Q1 (best quality fixed points) points with a 0.05 m grid overlain. The ellipse encompassing most data is approximately. 0.2m x 0.11m.

Data show that the single channel (L1) units have a relatively large area of scatter for an area that did not move during the data collection period (Figure 9). This is due to the L1 based GPS units being less accurate than more advanced counterparts, and the poor sky view of the rover unit (>50% of the sky is obscured on the RabT slope leading to poor satellite configurations). Improvements can be made on this by installing 2 channel (L2) units as well as moving the base station to the opposite valley side with a better sky view. New L2 circuit board units, which are cheaper than the Emlid L1 units, but were not available at the start of

the work, are currently being tested for deployment but require further research and development to complete a quality assessment.

3.6 Ground-Based Synthetic Aperture Radar (GB-SAR)

A concrete plinth has been installed on the forest track opposite the RabT slope (although this has recently been unseated by track re-grading machinery). A Meta-sensing GB-SAR was mounted on this plinth for three days across clear, cloudy and rainy conditions to assess the effectiveness of the system in detecting millimetre scale deformation (Figure 10A). The GB-SAR detects any deformation towards the instrument; Figure 10B shows the strength of the signal being returned from the forest track.

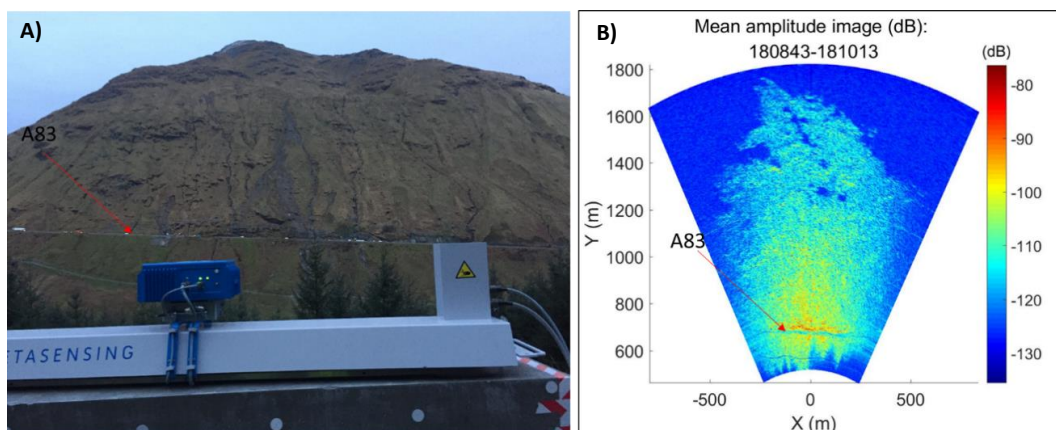


Figure 10 A) GB-SAR installed on concrete plinths facing the A83; B) Mean amplitude strength image generated

GB-SAR relies on coherence between scans, where there is significant activity (works, traffic) there is likely to be no coherent (useable) data. As expected in the deployment conditions there was no significant displacement detected in these data above/below road level, other than at road level where construction activity at the side of the A83 could be seen and coherence between data acquisitions was maintained (Figure 11).

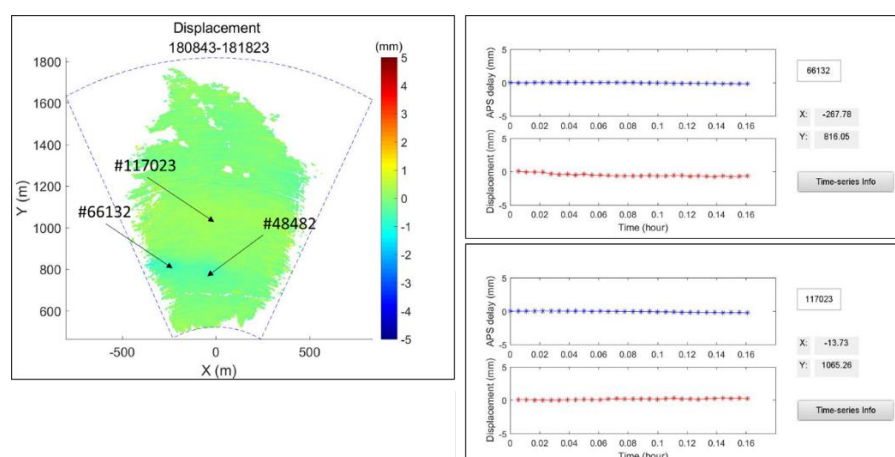


Figure 11 Displacement map from a 10-minute data acquisition in intermittent visibility conditions; three picked points illustrate the low levels of noise in these data; green colours in the map denote no change, with corresponding flat lines in the displacement graphs showing little variability on the y-axis across the 10 minute time series.

Data in Figure 11 show the stability of the time-series and processing algorithm. Further analyses will be able to use our existing TLS topographic data to both improve the GB-SAR processing and to geo-reference these data into a common coordinate system.

3.7 Terrestrial Laser Scanning (TLS)

Between March 2015 and November 2019 there have been 27 TLS scans of the slope; recent scans were conducted with a Riegl VZ400 TLS (Figure 12; Table 2). Spatial resolution for the scans is < 0.20 m since May 2018 when the VZ4000 came into operation. Change detection is conducted between consecutive scans to accurately visualise loss and gain of material on the slope (Figure 13) and calculate the magnitude of failures.



Figure 12 Riegl VZ4000 TLS being used from the forest track to scan the RabT slope

Cloud Compare M3C2 change detection software has been used to extract change between two consecutive scans and remove noise from the data such as vegetation growth/loss between scan epochs. A bespoke ArcGIS tool is then able to use the point cloud data from the M3C2 change outputs and calculate the area and volumes of the loss and gain of material.

Epoch based and cumulative change detection maps (Figure 13) can then be created within ArcGIS to highlight areas of higher activity on the slope and volume of material removed from the slope. These data can generate new hazard models for the slope and inform our understanding of the slope failure processes involved.

Table 2 A list of terrestrial laser scan data of the RabT held by Newcastle and Northumbria Universities

Year	Project	Scan date	Scanner	
2015	Bradley Sparkes' PhD	17th March	Riegl LMS Z620i	
		20 th April	Riegl LMS Z620i	
		29 th July	Riegl LMS Z620i	
		8 th September	Riegl LMS Z620i	
		16 th October	Riegl LMS Z620i	
		6 th December	Riegl LMS Z620i	
2016		11 th February	Riegl LMS Z620i	
		24 th May	Riegl LMS Z620i	
		26 th July	Riegl VZ4000	
		19 th September	Riegl LMS Z620i	
		26 th November	Riegl LMS Z620i	
		17 th December	Riegl LMS Z620i	
2017		29 th January	Riegl LMS Z620i	
		3 rd February	Riegl LMS Z620i	
		27 th April	Riegl LMS Z620i	
2018		Innovative Monitoring Contract	16 th November	Riegl LMS Z620i
			23 rd January	Riegl LMS Z620i
			24 th May	Riegl VZ2000s
	2 nd October		Riegl VZ4000	
	10 th October		Riegl VZ4000	
	15 th October		Riegl VZ4000	
	13 th November		Riegl VZ4000	
	26 th March		Riegl VZ4000	
2019	Innovative Monitoring Contract – No cost, time extension	29 th June	Riegl VZ4000	
		12 th September	Riegl VZ4000	
		3 rd October	Riegl VZ4000	
		1 st November	Riegl VZ4000	

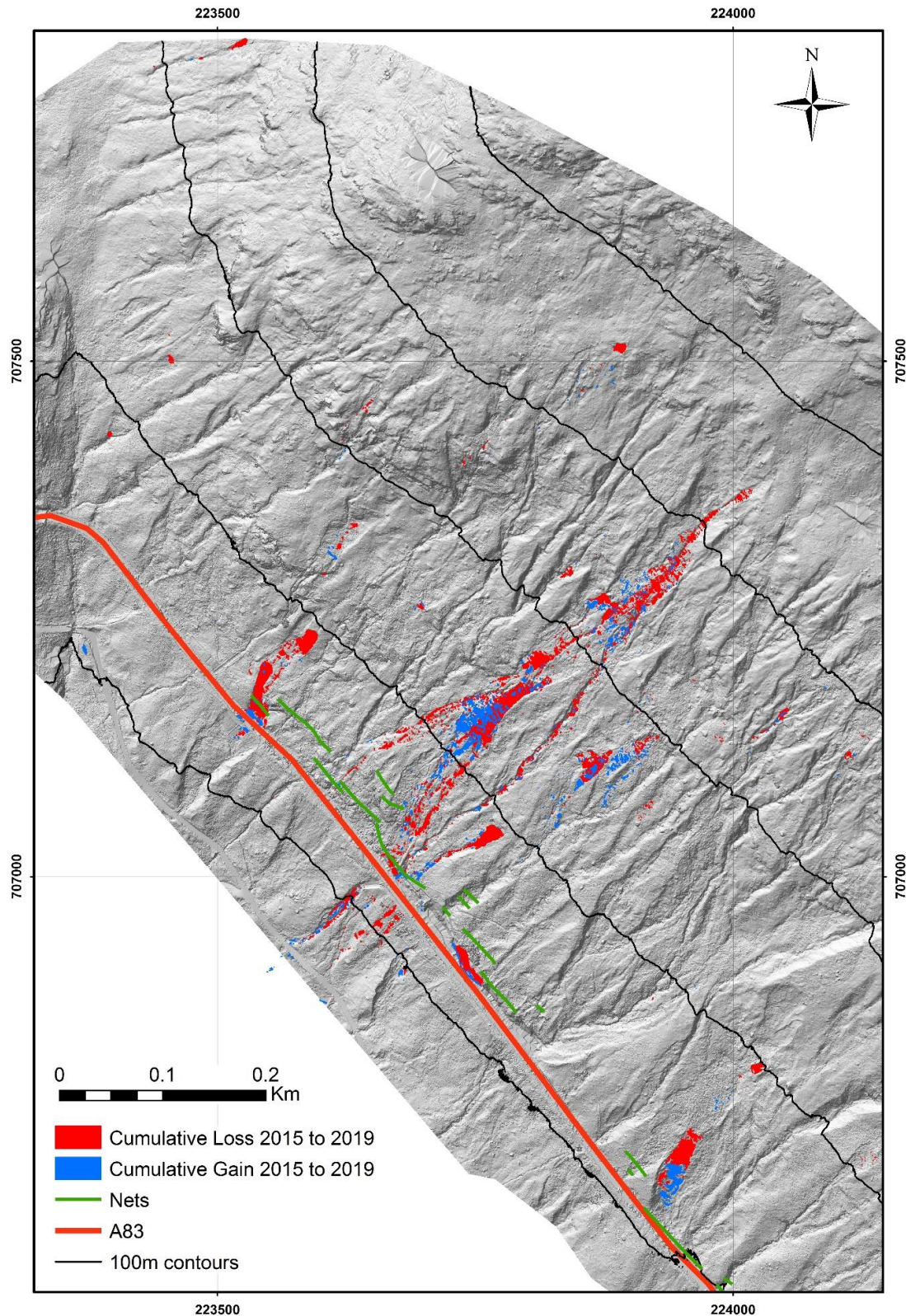


Figure 13 Terrestrial laser scanning data for the monitoring period March 2015 to September 2019. The map shows the cumulative loss and gain of material over the slope for the entire monitoring period. The data are draped over a digital elevation model (DEM) derived from the November 2018 point cloud data (widest coverage dataset) but DEMs exist for all laser scan dates

4 Innovative monitoring: Equipment pros and cons

Equipment	Purpose	Data interval	Pros	Cons
dSLR time-lapse camera	Optical imagery of the slope for manual or automated tracking of deformation/failure of slope material.	30 minutes	<ul style="list-style-type: none"> - Easily adapted to send data back in near real-time rather than manual download - Proven to be able to detect precursory movement on the slope during and after storm events. - Easy to maintain - Full frame camera images (36MP) 	<ul style="list-style-type: none"> - Currently manual download - 30 minute data – can only detect change every 30 minutes - Cannot see through cloud or at night
Trail cameras	Optical imagery of the slope for viewing large scale slope changes (failures)	15 minutes	<ul style="list-style-type: none"> - Images sent back to Newcastle in near real-time - Proven to be useful in determining landslide event timings – these cameras have been used to narrow down time-windows for events which can then be compared to other factors such as rainfall. - Takes an NIR image at dawn and dusk which can be used to detect new changes on the slope - Low-cost 	<ul style="list-style-type: none"> - Low resolution, 5MP on the unit and 2MP data sent back - Cannot see through cloud or at night
Weather station	Rainfall, rain intensity, wind and temperature data for actual on slope conditions rather than other gauges near the site.	Constant data but 5 minute web-based update rate	<ul style="list-style-type: none"> - Show actual on slope conditions. - Near real-time data - Can be used by the USGS forecast model to generate rain thresholds and alerts - Adaptable system where additional gauges can be added for relatively little expense 	<ul style="list-style-type: none"> - Currently requires mobile signal which can be intermittent (being upgraded to Wi-Fi)
Seismometers	Seismic monitoring from 4 stations on the slope. Debris-flows should be detected by these instruments and alarms sent to stakeholders	Millisecond	<ul style="list-style-type: none"> - 24 hour operation and detection of events, including night time and during bad weather - Streaming of data in real-time - Alarms trigger when an event is detected – seismic data from the event can be mobilised quickly for a review & response. 	<ul style="list-style-type: none"> - Large installation footprint (5-6m²) - Power hungry as they are constantly running - They require further research to threshold the event detection and minimise false alarms

dGPS	Base station and RTK rover station on the slope. Rover stations can be quickly deployed to areas of concern to record real-time deformation data.	Continuous	<ul style="list-style-type: none"> - Real-time streaming of data from the slope to a requested place - Centimetre accuracy - Low cost, and therefore rover stations may be considered 'disposable' if placed on an area that eventually fails. - Easy to deploy and therefore could have good spatial/temporal coverage of areas of concern. 	<ul style="list-style-type: none"> - Need to ID areas of concern (from time-lapse) then place instruments - Errors need constraining in order to avoid false alarms - Currently only L1 units (~20cm accuracy) but L2 (1cm accuracy) units are available to deploy.
GB-SAR	Detect near real-time, (potentially) millimetre scale slope deformation from a fixed installation on the forest track opposite the slope	Constant data collection with 10 minute change detection intervals	<ul style="list-style-type: none"> - Detection of millimetre scale slope deformation - Weather independent; however detection resolution is affected in bad weather. - Short time epoch for receiving change data - Can potentially be set up for near real-time data streaming 	<ul style="list-style-type: none"> - Expensive (>£200k) - Requires a lot of power - If deformation is too rapid then change detection will lose coherence and only record a void in the data. - Requires large, fixed concrete blocks for mounting – blocks were installed but have been dislodged from their mount during track regrading. - Line of sight deformation
TLS	Highly accurate 3D laser scans of the slope are produced; consecutive scans can be 'differenced' to produce an accurate model of change on the slope between the two scans used.	Epoch based scanning – on average every 4 months	<ul style="list-style-type: none"> - Accurate (10cm) slope models - Derived parameters from scans include: source/deposit volume, areas of scour, areas of deformation and cross-sectional areas. - Detection of 'missed' events - Proven and benchmarked data - Data has been used by Jacobs for their boulder study - Can confirm precursory movement detected by other methods 	<ul style="list-style-type: none"> - Reactive data collection, 'what has already happened' - Time intensive - Expensive for a fixed station - Will not penetrate cloud, limited ability to measure through rain
Tilt-meters	Record the tilt/movement of the sensor to assess whether the ground is moving	Continuous	<ul style="list-style-type: none"> - Very small and easily installed 	<ul style="list-style-type: none"> - Requires manual download - Data was not useful as the instrument appears to have been too sensitive to external forcing such as wind, frost-heave, vegetation etc.

5 Equipment recommendations and future directions

The items of equipment that have been installed and tested at the RabT, along with their installation locations are shown in Figure 14. Recommendations for each item are given below.

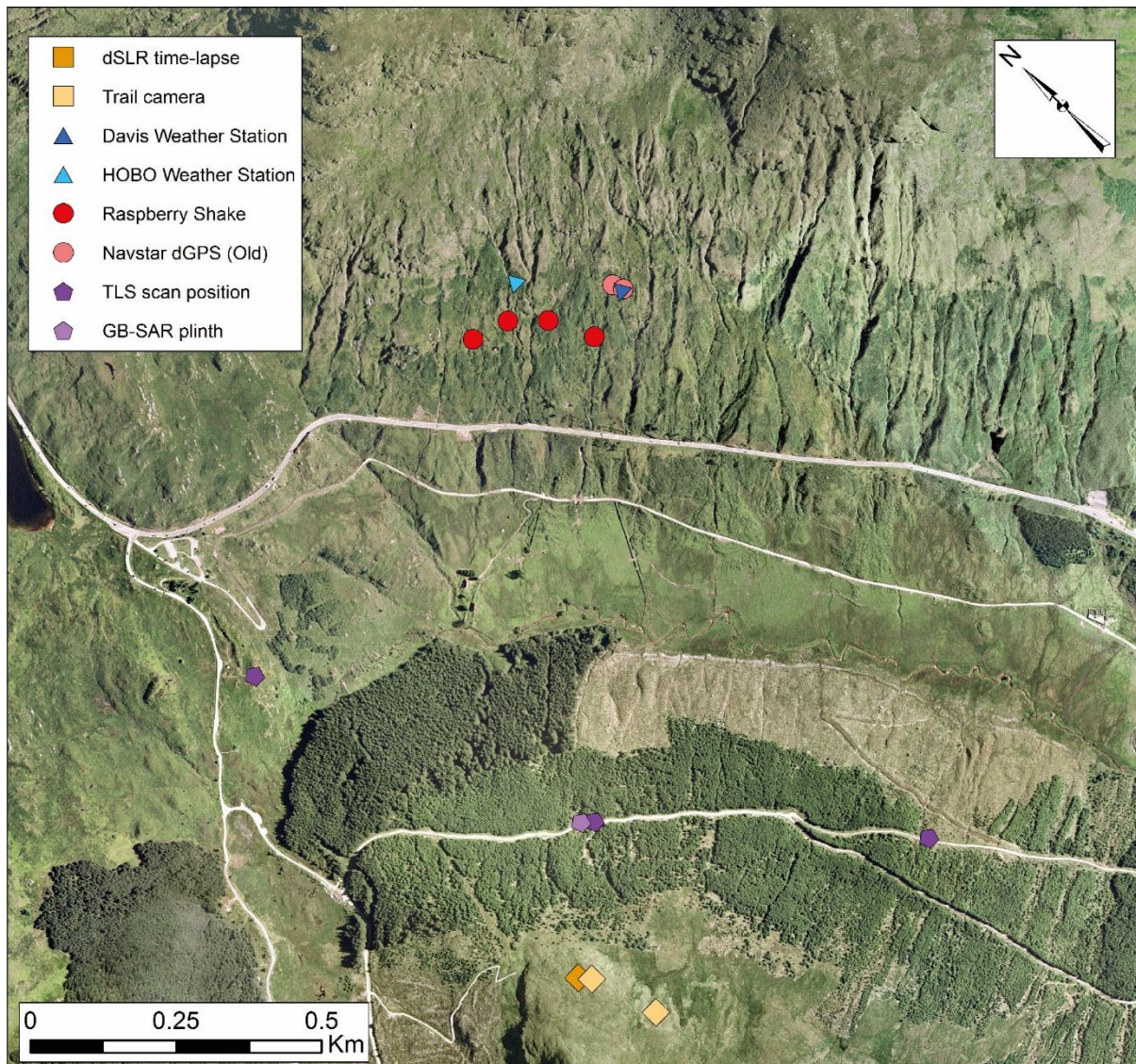


Figure 14 Locations of installed equipment in Glen Croe

dSLR time-lapse camera: Recommended for immediate consideration in operational monitoring of unstable slopes. This equipment is operationally ready and will provide cost-effective essential slope change data to future monitoring strategies. Whilst the manual download of data has been useful, any future installations should consider near real-time data transmission. Research needs to be completed on making deformation tracking an automated process between images. There is one dSLR station facing the slope and we recommend leaving it installed and supporting future maintenance.

Trail cameras: Recommended where qualitative and high temporal resolution data on slope conditions are critical. Trail cameras provide low cost and very easily deployed imagery but low resolution images hamper the detection of any small slope failure events. The advantage of these units over the dSLR time-lapse is their lower cost and the near real-time data transmission; however, this will be superseded by a new streaming dSLR time-lapse (data transmission costs will be higher). Future work should explore the use of near-infrared (NIR) camera technology to monitor the slope in low-light conditions. There are two near real-time streaming trail cameras facing the slope, we recommend leaving them installed until they are superseded by the dSLR.

Seismometers: Recommended as a likely future monitoring approach for both slope movement and changes in slope subsurface conditions. These instruments allow continuous, weather independent, 24 hour monitoring of the slope. They can be fitted with Wi-Fi/3G capabilities in order to stream data and create alert systems for slope management. One station installed during October 2018 did detect one of the debris-flow events, however restrictions on deployment locations due to the land sale meant that this data was not ideal. A network of four, well placed instruments is currently monitoring the slope. We recommend the seismometer installations should remain in place and be maintained so that data on ambient ‘noise’ and characteristic debris flow signals can be collected. The network could be extended if more areas of risk were identified.

Weather stations: Recommended for immediate consideration in operational monitoring of unstable slopes. A network of rainfall sensors should ideally be placed across the problem slope to examine differential slope conditions. Data should be analysed through the USGS ‘Thresh’ (or similar) software to provide intelligent alerts to stakeholders of higher-risk conditions on the slope. Piezometer data could compliment the weather station data in determining local ground-saturation thresholds for slope failures but at the RabT ground water appears to be highly variable and channelized so caution should be exercised. The single weather station on the slope has been able to record continuous rainfall, wind, and temperature data for over a year with derived rain intensity measurements. Data comparison with the SEPA Loch Restil gauge has shown that the RabT receives significantly different weather conditions to that of surrounding areas. The Met Office made the following comment regarding the RabT after the October 2018 events:

“It would be good to have some site analysis carried out to identify site specific characteristics of the RBT, for example how certain wind directions affect the expected rainfall amounts - whether there is orographic enhancement or shelter from particular directions. This could then be used to improve the forecast.”

We have recently trialled a profile of three weather stations on site that should help inform and refine understanding of potential orographic effects on rainfall dispersion across the slope. Although beyond the scope of this study, findings and data will be available to Transport Scotland.

TLS: Recommended for immediate consideration in operational monitoring of unstable slopes. These data identify active areas, establish patterns and sequences and enable future projections of slope movements, and thus are valuable for any future slope monitoring strategy. TLS data have enabled the detection of slope failures that did not reach the road and therefore remained undocumented but could remobilise or propagate in subsequent events. The data allow the extraction of debris flow volumes and source area shapes which may help us understand the processes working on the slope. The project has continued a well-established approach, combining regular surveys with responsive change detection data collections, we strongly recommend this continues.

GB-SAR: The GB-SAR requires further testing to ascertain its viability for slope monitoring. It is suited to sites with high value assets / high loss potential due to equipment costs and power considerations. Initial tests show that the Fast GB-SAR is able to detect millimetre deformation on the slope from the Forest Enterprises track by collecting radar images of the slope every 10 minutes. Two concrete slabs were installed on the forest track to support the instrument, but these have been displaced during the regrading of the track. A long term installation has not been tested and ideally the instrument would be deployed during a storm or other high-rainfall event to test the real-time detection of on-slope deformation.

dGPS: Recommended for consideration in unstable slopes where potential areas of precursory movement, or, boulders of concern can be accessed. Single-channel L1 dGPS units have shown promise in live data streaming and relatively good position accuracy (~0.20 m). However, greater accuracy is required to track real-time slope deformation and avoid false alarms. New 2-channel L2 dGPS units are now available that should provide sub-centimetre accuracy and can be deployed if any precursory movement is detected from the TLS or dSLR time-lapse analyses.

6 Summary

The aim of the Innovative Monitoring Strategies project has been to implement a novel multilevel modular monitoring system to detect landslide activity prior to, during and after landslide events, providing a business case for appropriate monitoring to enable cost-effective management of hazardous slopes in Scotland. Through this research, new monitoring techniques have been developed and deployed at the A83 Glasgow–Argyll road at the RabT, satisfying the objectives that were stated in Section 2.

Some of the tested technologies are found to be operationally ready and of clear and cost-effective benefit and hence are recommended for immediate implementation, whilst others are likely to yield valuable new monitoring data with further development/research phases prior to becoming operational options.

The outcomes of this project are directly applicable to Transport Scotland's future management of the RabT but will also be of potential benefit to other locations on the Transport Scottish network, such as A82 Glen Coe, and those of other road authorities that are susceptible to landslides. The selection of appropriate techniques, or combination of techniques, for the monitoring of other locations prone to landslides and the frequency of monitoring is likely to be influenced by the geology and geomorphology of the individual slopes.

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The aim of the Innovative Monitoring Strategies project has been to implement a novel multilevel modular monitoring system to detect landslide activity prior to, during and after landslide events. Through this research, new monitoring techniques have been developed and deployed at the A83 Glasgow–Argyll road at the “Rest and Be Thankful” (RaBT); the RaBT is perhaps the most challenging site managed by Transport Scotland where steep slopes above the road are susceptible to repeated landslides. Some of the tested technologies are found to be operationally ready and of clear and cost-effective benefit and hence are recommended for immediate implementation, whilst others are likely to yield valuable new monitoring data with further development/research phases prior to becoming operational options.

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