Institution: Newcastle University		
Unit of Assessment: 14 Geography and Environmental Studies		
Title of case study: Building Infrastructure Resilience Through Innovative Monitoring and Forecasting of Landslide Hazards in the North of the UK (Scottish Highlands and Cumbria)		
Period when the underpinning research was undertaken: 2010 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Stuart Dunning	Reader	2015 –
Rupert Bainbridge	Post-Doctoral Researcher	2017 –
Andrew Large	Professor	1994 –
Andrew Russell	Professor	2004 –
Anne-Sophie Meriaux	Reader	2007 – 2020
Period when the claimed impact occurred: August 2015 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Landslides that affect roads are life-threatening and lead to negative social and economic impacts because of travel disruptions and road closures. The ability to predict effectively landslide threats reduces these harmful outcomes. The A83 “Rest and Be Thankful” in Argyll and Bute is one of the most at-risk, landslide-prone roads in the UK. Research at Newcastle has led to the development of novel live streaming low-cost sensors and data processing systems which have been adopted by Transport Scotland and their contractors. This has resulted in: (i) improvements in the monitoring of the A83 road in Scotland, with the consequence of **reduced risk of harm** to road users and operators; (ii) adoption of **improved monitoring and management strategy** for landslide-prone sites by Transport Scotland for wider Scottish road networks; and (iii) implementation of the novel landslide monitoring system in Cumbria, **alleviating risk to buildings and transport infrastructure**.

2. Underpinning research

The ability to forecast whether a landslide is likely to occur, or is occurring, and where it will impact, is critical for public and private organisations who manage and maintain road and rail infrastructure. There is a balance to be struck between ensuring the safety of road users and the economic and social consequences of road closures, which can be highly disruptive for local residents and businesses. Standard monitoring approaches rely on (i) visual detection of a final landslide event by staff/road users; and (ii) threshold rainfall conditions based on often uncertain timings of past landslide events. Landslides often finally occur after extensive precursory movement, usually too small to be reliably seen, driven by rainfall.

Researchers in Newcastle University’s Physical Geography research group led by Dunning with Russell, Large, Bainbridge and Meriaux studied how interrogating real-time data from innovative technological developments can inform more effective decision-making. This is driven by novel, low-cost methods and sensors that can forecast periods of likely landslide activity and detect the precursors to landslides days before final failure.

This research began by developing terrestrial laser scanning (TLS) methods to detect changes in a landscape (as materials move around) and derive the volumes of these changes. The next step, critical for understanding hazard and risk, was to reveal the sequences of events that make up the ‘final’ change – the impact of one large event versus 10 small events with the same cumulative volume is very different. Our innovation was to combine TLS and time-lapse camera analyses for the major Eyjafjallajökull eruption in Iceland which triggered ‘hyper concentrated flows’ (water-rich landslides) in 2010 [**PUB1, G1**]. The ability to detect even small-scale change and to put reliable volumes and times on these changes was further developed with drone derived 3D data [**PUB2**]. This research sparked the interest of Transport Scotland (TS) and the UK government’s Transport Research Laboratory (TRL), who wanted to understand better the size and frequency of mobile/water rich 'debris flows' on 'at risk' Scottish slopes. Collaborative research started with a Scottish Roads Research Board (SRRB) funded project [**G2**].

Building on research on damaging landslides triggered by Storms Desmond and Frank (2015-16) [**PUB3**], Newcastle was awarded a further NERC Urgency Grant [**G3**] to apply high-resolution change detection and time-series analyses to pre- and post-storm 3D TLS data. This set up the relationship with TS and TRL [**PUB4**], leading to two further research projects [**G4-5**] funded by the SRRB. This work focused on moving from proof-of-concept research to operational ready techniques benchmarked against industry standards to alert stakeholders to 'landslide more likely' and 'landslide now', also integrating seismic detection and location approaches derived from iceberg fracturing, analogous to landslides [**PUB5**].

These scientific advances, particularly as applied to the series of road-closing landslides in October and November 2018 during Storm Callum, led to a Joint Technical Workshop, led by TS, with other industry and Government stakeholders in March 2019 where a series of future monitoring options were presented for the first time [**PUB6**]. These findings formed the basis of a successful NERC award, 'Constructing a Digital Environment Feasibility Study' [**G6**], in partnership with TS, which has enabled us for the first time to detect automatically deformation in tracking time-lapse camera imagery and record precursors (10-20 days) to landslides. Combining this with refinement of low-cost seismic sensors that detect, track [**PUB6**] and time events, innovatively modified to run off-grid and stream over a resilient slope wide WiFi network, led to an additional award from Research England's Connecting Capabilities Pitch-In programme [**G7**]. The Pitch-In grant is focused on the Internet of Things (IoT) and has developed low cost dGPS units for 24/7 information at near disposable costs to stream live data, along with low-cost fixed terrestrial laser scanners. These technologies have the advantage of producing 24/7 data sized low enough to send over a mobile connection.

A further project [**G8**] involves integrating feasibility data derived from 24/7 monitoring [**PUB6**] into forecasting and detection tools for TS. By streaming slope-wide rain gauges from which we have refined thresholds of 'event likely' from our knowledge of the timing and onset of past landslides, alongside seismic data and novel camera-based feature tracking, we have evidenced the impact of hyper-local rainfall intensity-duration relationships for landslide triggering. This has led to improved fore- and now-casting for increased periods of landslide hazard [**PUB6**]. Our data are now held in the British Geological Survey National Landslide Database and represent a step-change in the granularity of data – for example, a landslide event that previously would have been recorded as 'one' is shown by our research to be a series of 13, each with a unique relationship to the triggering rainfall. This is redefining understanding of the conditions that drive slope instability at a national scale.

3. References to the research

[**PUB1**] **Dunning, S. A.**, **A. R. G. Large**, **A. J. Russell**, M. J. Roberts, R. Duller, J. Woodward, **A. S. Meriaux**, F. S. Tweed & M. Lim (2013). The role of multiple glacier outburst floods in proglacial landscape evolution: The 2010 Eyjafjallajökull eruption, Iceland. Geology 41(10): 1123-1126. https://doi.org/10.1130/G34665.1.

[**PUB2**] Westoby, M. J., **Dunning, S. A.**, Woodward, J., Hein, A. S., Marrero, S. M., Winter, K., and Sugden, D. E. (2016). Interannual surface evolution of an Antarctic blue-ice moraine using multi-temporal DEMs. Earth Surface Dynamics 4, 515–529. https://doi.org/10.5194/esurf-4-515-2016.

[**PUB3**] Sparkes, B., **Dunning, S.**, Lim, M. & Winter, M.G. (2017), Characterisation of Recent Debris Flow Activity at the Rest and Be Thankful, Scotland. in M. Mikoš, V. Vilímek, Y. Yin & K. Sassa (eds), Advancing Culture of Living with Landslides: Landslides in Different Environments. vol. 5, Springer, pp. 51-58. https://doi.org/10.1007/978-3-319-53483-1_8.

[**PUB4**] Winter, M.G., Sparkes, B., **Dunning, S.A.**, & Lim, M. (2017). Landslides Triggered by Storm Desmond at the A83 Rest and be Thankful, Scotland Panoramic Photography as a Potential Monitoring Tool. TRL Pub. Project Report, 2017: PPR824. ISBN: 978-1-910377-77-2. [Available on request via TRL website]

[**PUB5**] Kirkham, J. D., N. J. Rosser, J. Wainwright, E. C. Vann Jones, **S. A. Dunning**, V. S. Lane, D. E. Hawthorn, M. C. Strzelecki & W. Szczuciński (2017). Drift-dependent changes in

iceberg size-frequency distributions. Scientific Reports 7(1): 15991. 91) https://doi.org/10.1038/s41598-017-14863-2.
[**PUB6**] **Bainbridge, R.**, **Dunning, S**., Lim, M. (2020) Innovative monitoring strategies for managing hazardous slopes. TRL Pub. Project Report, 2020: PPR963. ISBN: 978-1-913246-47-1. [Available on request via TRL website]

[**G1**] 2010-2011. **Russell (PI)**, **Large**, Liang, **Meriaux**, Carrivick, **Dunning,** Impacts and dynamics of volcanically-generated jökulhlaups [glacial run], Eyjafjallajokull, Iceland. NERC Urgency NE/I007628/1 (GBP64,000).
[**G2**] 2014-2017. **Dunning (PI)**, Lim, Winter, Strategies for managing hazardous slopes I. SRRB (GBP90,000).
[**G3**] 2016-2017. **Dunning (PI)**, Winter, Lim, Landslides triggered by Storm Desmond at the A83, Rest and Be Thankful, Scotland. NERC Urgency NE/P000010/1 (GBP46,000).
[**G4**] 2017-2019. **Dunning (PI)**, Lim, Winter, Strategies for managing hazardous slopes II. SRRB (GBP55,000).
[**G5**] 2020-2022. Landslide Forecast, Detection, Notification. SRRB (GBP85,000).
[**G6**] 2019-2020. **Dunning (PI)**, **Bainbridge**, Landslide Mitigation Informatics (LIMIT): Effective decision-making for complex landslide geohazards. NERC NE/T00567X/1 (GBP120,000).
[**G7**] 2019-2021. **Dunning (PI)**, Managing hazardous slopes using resilient IoT sensors and real-time processing (slopeRIoT). Research England 'Pitch-In' (GBP55,375).
[**G8**] 2020-2022. **Dunning (PI)**, **Bainbridge**, Lim, Winter, SRRB (GBP85,000).

PUBS 1-2 and 5 are in peer reviewed journals and **Grants 1, 3, and 6** result from peer review.

4. Details of the impact

The A83 "Rest and Be Thankful" is a chronic hotspot of UK landslide activity. It is the most at-risk road in Scotland for TS, who are responsible for the safety of road users and the continuity of service through a series of Operating Companies (OCs, currently BEAR Scotland). The most serious human consequences of landslide events are serious injuries and fatalities. However, there are additional issues such as costs associated with clean up, repair, search and rescue, disruption to infrastructure because of road closures and diversions, and impacts on the lives of local people and transport-dependent sectors such as tourism. Furthermore, these can lead to a longer term 'vulnerability shadow' being cast over landslide-prone areas, which can create a scarring effect on the local economy.

Analysis by TRL of 4 Scottish landslide events between 2004 and 2007 (including one on the A83) estimated that the direct costs per event ranged from GBP400,000 to GBP1,700,000, while the direct consequential costs ranged between approximately GBP180,000 and GBP1,400,000. Given that these costs will have escalated since their original calculation and do not include indirect consequential costs, the negative consequences of landslide events are substantial. As such, more effective methods for accurate prediction of landslides will have significant benefits for the 4,000 daily users of the A83 as well as the residents and businesses in the 2,800km^2 area it serves. Working in collaboration with TS and its contractors, the research has had the following 3 key impacts:

(i) Improvements in the monitoring of one of Scotland's major roads (the A83) at greatest risk from landslides. This has reduced risk of harm to road users and operators.
The Geotechnical Manager TS has summarised our period of impact: '*The use of innovative monitoring technologies has provided us with a new understanding of the changes on the slopes in space and time and allowed us to strategically manage the hazards and risks in a better, more informed manner that was not possible before. Specifically, locating new areas of concern prior to failure has allowed direct interventions such as the deployment of landslide survey teams from our Operating Company to assess risk*.' [**IMP1a**]. TS further explains that, '*The monitoring systems established by Dr Bainbridge and the University of Newcastle team are not only proving their value as a key element to be built into our long-term management strategy for the Rest and Be Thankful corridor, but they have also played an active role in the day-to-day management of the present on-going landslide events*' [**IMP1b**].

Impact work began in October 2015 when the Head of Ground Engineering at TRL contacted the team at Newcastle, requesting our expertise based on research from **G1** published in **PUB1**, as they recognised the need '…*to make some clear decisions on which instruments to keep/maintain and which to effectively abandon with full justification for decisions in either direction. [Your input] would be extremely useful to this process*' [**IMP2**]. In December 2015 and January 2016, rainfall during Storm Desmond and Storm Frank triggered landslides that closed the A83 for several days with a landslide hitting a moving vehicle. The monitoring in place along with unique Newcastle-led pre-event data [**G3**] allowed for quantification of the landslides and an analysis for TS of future approaches [**PUB2-3**]. In the wake of these events, the Newcastle researchers were commissioned to lead a TS-directed SRRB project [**G4**] to install novel low-cost seismometers and develop feature tracking time-lapse cameras, building on earlier research findings [**PUB1,3-4**], reported in [**PUB5-6**].

In October/November 2018 Storms Ali and Callum triggered landslides at the "Rest and Be Thankful" hotspot that closed the A83 and the Old Military Road (a local diversion used to eliminate the maximum possible 60-mile diversion) below it for 9 days. 10 days prior to these events, Newcastle's team alerted TS to precursory movement on the slope, detected using the developed time-lapse feature tracking research, leading to direct interventions in management of the road. TS state: '*This warning allowed us to assess the works in progress at that time for the installation of a further phase of physical mitigation measures, resulting in the rearrangement of the works and traffic management measures to ensure that traffic was not held stationary beneath areas of specific concern on the slope. Landslides then occurred as forecast, closing the road but without harm to road users and operators*.' [**IMP1a**].

Continued analyses of time-lapse imagery datasets revealed that the event was a sequence of 13 landslides, each of which could have their timing relative to our measured rainfall quantified and categorised into those resulting from long duration rainfall and those resulting from short intense rainfall. Continued updates were requested by the stakeholders, of which TS said: '*In the immediate aftermath of the landslide, this research then provided key information on the sequence of events, volumes, and timings and identified residual areas of instability that we then rapidly communicated to our Operating Companies enabling them to operate more safely and effectively*'. [**IMP1a**]

Based on the evidence of the efficacy of Newcastle's approach, TS, after a stakeholder meeting in November 2020 discussing urgent actions for the A83 (disseminated as **IMP3**), have since funded and maintained 4 deformation-tracking dSLR cameras using Newcastle's processing methodology and have also adopted the resilient site-wide Wi-Fi, initially funded through **G6-7**. The operating company, BEAR, routinely request updates on the research team's live-processed rainfall data in order to make data-informed choices on landslide patrols and road opening/closing. These choices form the basis of daily stakeholder (and press) information releases, including providing updates to TS's more than 300,000 followers on Twitter [**IMP4**]. A Met. Office report commissioned by TS [**IMP5a-b**] in the aftermath of Storms Ali and Callum, when reporting on the Newcastle rainfall system for predicting periods of enhanced landslide activity to forecast raised threat levels, concluded that: '…*the Newcastle gauge is the one utilised most by those on site…' and '…so forecasting values which relate best to this [Newcastle system] would be the most beneficial*' [**IMP5b**]. This was taken forward in 2019/20 and our rainfall sensors are now used operationally to determine on-slope rainfall amounts. The deformation tracking/time-lapse camera and rainfall sensor network data are both hosted live where they can be accessed by the Operating Company and their subcontractors to inform their decision-making on a day-to-day basis [**IMP4**]. Rainfall data are now also being used in a 'shadow trial' to refine the operation of warning lights for road users after evaluating thresholds that trigger the alerts [**PUB6**].

After the August 2020 landslides, which resulted in the A83 being closed for 125 days, a further stakeholder meeting used our research developments [**IMP3** slides 20/21] and a key outcome was to fund the adoption and extension of this deformation monitoring [**IMP3** slide 25] to inform decision-making as to when to keep the A83 / Old Military Road open, and when to close the road for safety. Our research has developed disaster resilient live data streaming [**G6,7**] now adopted by BEAR at the A83 on behalf of TS [**IMP1a,4**]. We have been requested to provide training/designs to both BEAR and Geo-Rope in how these systems can be deployed and maintained, resulting in an A83 TS-funded maintenance programme [**IMP4**], making 'Newcastle University research fully operational as part of our decision making to reduce threats to road users' [**IMP1a**]. Our findings have been cited by the Chair of SRRB in *Transportation Professional,* the magazine of the Chartered Institution of Highways and Transportation (CIHT), with broad reach (in excess of 13,000 members) [**IMP6**].

(ii) Adoption of improved monitoring and management strategy for landslide-prone sites by TS for wider Scottish road networks.
This research has effectively driven the development of new integrated and hierarchical networks of sensors [**PUB5**], most of which are not conventionally used in monitoring and managing landslide hazard for acute events. The result is that the A83 is the most densely monitored slope in Scotland, at a far lower cost than more conventional systems [**IMP4**]. In addition, low level (fixed interval repeat laser scanning/change detection) monitoring has been undertaken at 2 other high hazard sites across Scotland [**IMP1a**].

After Storm Callum, TS instigated a Joint Technical Workshop for industry and Government stakeholders (March 2019). At this workshop, and a subsequent SRRB workshop (January 2020), the Newcastle team presented their innovative approaches to the long-term monitoring options at Scottish landslide sites. Following consultation with the key stakeholders after these events, and demonstrating the extended reach of the research impact, TS said that '*Following the recent events, new insights from this research have directly changed the future monitoring and management strategy for landslide-prone sites such as the Rest and Be Thankful, and now form a best-practice case for adoption to the wider road network*'. [**IMP1a**].

(iii) Implementation of the novel landslide monitoring system in Cumbria, alleviating risk to buildings and transport infrastructure.
Extending the reach of our research impact, in April 2018 the Newcastle team was asked by the British Mountaineering Council (BMC) to install their streaming monitoring systems at Castle Rock of Triermain in the Lake District, a popular climbing crag on land owned by United Utilities, which threatened United Utilities infrastructure, a number of houses, and the B3352. Our research on failure prediction was used to word warning signs more appropriately and alert stakeholders to increasing risk [**IMP7**]. Final failure occurred in November 2018, with our monitoring cited on BBC news and the BMC website (15,700 reads [**IMP8a-c**]), resulting in an invitation to share best practice monitoring in the 2019 Cumberland Geological Society Annual Lecture (Dunning). As a result, the Newcastle team were invited to assess Cumberland County Council (CCC) roads threatened by landslides to deploy our solutions; and by the British Mountaineering Council to deploy at further hazardous climbing sites. 4 sites across Cumbria are due data streaming sensors (COVID-19-delayed from agreed 2020 dates, see **IMP7,9** and **COVID-19 statement**), to be part-funded by CCC [**IMP9**].

5. Sources to corroborate the impact

[**IMP1a-b**] Letters of support from TS Geotechnical Manager for, a) this ICS; b) NERC Fellowship grant in review.
[**IMP2**] E-mail, 8 October 2015 from former Head of Ground Engineering at TRL.
[**IMP3**] TS Stakeholder Presentation, 18 November 2020: https://tinyurl.com/TSstakeholder
[**IMP4**] Letter of support from BEAR Scotland: Minor Improvements Manager.
[**IMP5a-b**] a: Met. Office e-mail request for data; b: Met Office report commissioned by TS.
[**IMP6**] *Transportation Professional*, November-December 2020, p18-19.
[**IMP7**] Letter of support from the Access & Conservation Officer, British Mountaineering Council.
[**IMP8a-c**] Webpages from a: BBC; :b-c BMC, citing the formative influence of this research.
[**IMP9**] E-mail from Cumbria County Council: Economy & Infrastructure Directorate.