Institution: Loughborough University		
Unit of Assessment: C13 Architecture, Built Environment and Planning		
Title of case study: Saving lives and protecting infrastructure with novel low-cost landslide early warning systems		
Period when the underpinning research was undertaken: 2000 to 2018		
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:**
Neil Dixon	Professor of Geotechnical Engineering	1/10/1999 to date
Alister Smith	EPSRC Research Fellow Lecturer in Civil Engineering Senior Lecturer in Civil Engineering	1/10/2015 to 31/1/2017 1/2/2017 to 30/4/2020 1/5/2020 to date
Period when the claimed impact occurred: 2014 to 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

Globally, landslides kill thousands of people annually and damage critical infrastructure costing billions of pounds. Warnings for vulnerable communities are seldom provided due to the prohibitive costs of traditional monitoring. Research has developed a novel lower cost early warning approach that ‘listens’ for landslides. Three impacts have been produced: **1)** *Improved public safety and infrastructure protection via affordable and increased landslide knowledge in UK, Italy, and Canada*; **2)** *enhanced community resilience to landslides in Myanmar and Malaysia*; and **3)** *the world’s first commercial, acoustic emission slope monitoring system*, developed with a global leading geotechnical instrumentation company.

2. Underpinning research (indicative maximum 500 words)

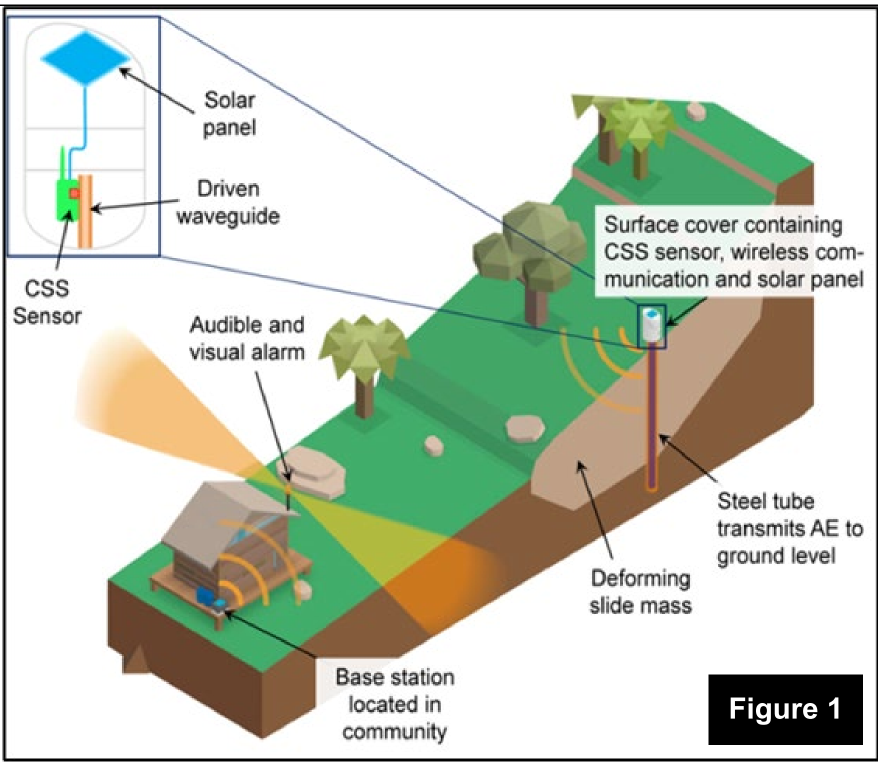
Affordable landslide early warning solutions are needed globally to protect vulnerable communities and to monitor critical infrastructure. Research undertaken at Loughborough University by Professor Dixon and Dr Smith, funded by three EPSRC grants, a Knowledge Transfer account, and two EPSRC Impact Acceleration Awards (IAA), addressed both challenges. We demonstrated that the acoustic emissions (AE) (i.e., high frequency noises) generated when slopes deform can be detected and interpreted to provide early warning of impending landslides. The owners of critical infrastructure can thus mitigate potential damage and people in harm’s way can be evacuated.

Our research established a quantified relationship between AE and displacement rates for deforming slopes. A practical approach was designed, using an *active waveguide* installed in a slope. The guide comprises a steel tube intersecting the failure surface with granular backfill placed to either surround or infill the tube. When the slope starts to fail, straining the active waveguide, AE generated by waveguide deformation is transmitted by the tube to the surface. The AE are then detected and quantified by a sensor that generates and communicates an alarm. Research established that measuring AE can detect landslides before inclinometers, which is the standard approach to monitor slopes.

We developed and assessed two AE systems through laboratory experiments and field trials: 1) since 2010, the Slope ALARMS (SA) system was developed to monitor slopes that threaten infrastructure (i.e., road, rail, properties), with functionality of remote data access and automatic generation of warnings to decision makers; 2) since 2016, the Community Slope SAFE (CSS) system was developed specifically to provide low-cost protection to vulnerable communities. Installed and operated as shown in Figure 1, it was designed for low manufacturing cost and to be maintained by the community. CSS delivers a landslide warning directly to the affected community via an audible/visual alarm.

The research to create the AE monitoring strategy, SA sensors and undertake field trials of the alarm system, enabled Dixon and Smith to deliver several world firsts:

- A framework was produced based on 62 laboratory tests [**R1**] and 5 large scale landslide simulations (accelerating deformations from 3.6 to 360 mm/hr) [**R2**] to establish interpretation of AE generated by deforming active waveguides and derive landslide velocities.



- SA sensors were deployed in a moving landslide proving that AE rates can be used to quantify slope displacement rates continuously and in real-time; achieved using analysis of 6 events with 1059 AE/displacement measurements using SA sensors and state-of-the-art inclinometer technology [**R3**].
- Studies of attenuation mechanisms demonstrated that AE could propagate tens of metres along waveguides [**R4**], proving they can monitor landslides with deep shear surfaces (e.g., 16 metres [**R5**]).
- An extensive series of field trials established the efficacy and practicality of the AE monitoring approach. 21 SA sensors installed at 12 slopes in 4 countries (UK, Italy, Canada & Austria) measured AE continuously for 131 years total monitoring [**R5**]. AE rates were proportional to slope displacement rates in all cases.

Research on the CSS sensor was designed using knowhow gained from operation of the SA system. Its performance was demonstrated via a series of laboratory simulations employing waveguides with infill to generate AE [**R6**]. A lower cost easier to install driven waveguide was used as it does not require a drilling machine. To test the system, seven CSS sensors were installed at three slopes in Myanmar (via funder FHI 360) and Malaysia (via EPSRC Global Development Funding), measuring AE continuously for a total of 12 monitoring years. The CSS systems were installed and operated by community groups trained by Dixon and Smith. This research demonstrated comparable performance to the SA system [**R6**] and proved the viability of the community led monitoring approach.

3. References to the research (indicative maximum of six references)

R1. Smith, A. & Dixon, N. (2014). Quantification of landslide velocity from active waveguide generated acoustic emission. Canadian Geotechnical Journal, 52(4), 413-425, DOI 10.1139/cgj-2014-0226.
R2. Smith, A., Dixon, N. & Fowmes, G.J. (2017). Early detection of first-time slope failures using acoustic emission measurements: large-scale physical modelling. Géotechnique, 67, 2, 138-152. DOI http://dx.doi.org/10.1680/jgeot.15.P.200.
R3. Smith, A., Dixon, N., Meldrum P., Haslam, E. E. & Chambers J. (2014). Acoustic emission monitoring of a soil slope: Comparisons with continuous deformation measurements. Géotechnique Letters 4(4), 255-261. DOI 10.1680/geolett.14.00053.
R4. Smith, A., Dixon, N. & Fowmes, G.J. (2017). Monitoring buried pipe deformation using acoustic emission: quantification of attenuation. International Journal of Geotechnical Engineering, 11, 4, 418-430. DOI 10.1080/19386362.2016.1227581.

R5. Dixon, N., Codeglia, D., Smith, A., Fowmes, G.J. & Meldrum, P. (2015). An acoustic emission slope displacement rate sensor – case studies. Ninth Int. Symposium on Field Measurements in Geomechanics, Sydney, Sept., pp 14. https://hdl.handle.net/2134/19021.
R6. Dixon, N., Smith, A., Flint, J.A., Khanna, R., Clark, B. & Andjelkovic, M. (2018). An acoustic emission landslide early warning system for communities in low- and middle-income countries. Landslides, 15:1631–1644. DOI 10.1007/s10346-018-0977-1.

The publications arose from competitively awarded UKRI EPSRC funding comprising responsive mode, KTA and IAA grants (£437k, 2005 to 2017). Recognition of the originality, quality and significance of the research underpinning AE slope monitoring is proven by inclusion of Slope ALARMS in the EPSRC *20th Anniversary Pioneer Magazine* celebrating research highlights in the decade 2004-2014 and identifying potential for impact. R1 to R4 & R6 are published in leading international journals which operate rigorous peer review. R3 was named 'best paper of the year' published in *Géotechnique Letters* and was awarded the *Thomas Telford Premium*. R5 was published in the proceedings of the leading international conference on geotechnical instrumentation and is included as it summarises the combined results from field trials in 4 countries at 12 slopes.

4. Details of the impact (indicative maximum 750 words)

Research by Dixon and Smith identified and addressed a global need to deliver affordable approaches for early warning of landslides to protect vulnerable communities and critical infrastructure. The research was the focus of TV programmes (e.g., *Discovery Channel Daily Planet*, 2014; *BBC Inside Out*, 2016); received multiple awards (e.g., *The Engineer Technology and Innovation Awards 2011*, *Institution of Civil Engineers Merit Award 2015*, *Hawley Award 2015, 2019 Philip Leverhulme Prize in Engineering;* a LU *2017 Enterprise Award* – with 1100 public votes); generated public, industry, and stakeholder enquiries from 26 countries leading to invited prestigious lectures (e.g., British Geotechnical Association), and an article in a global technical practice journal (*Geotechnical Instrumentation News*, December 2016). Novelty and world leadership was demonstrated through UK patent GB 2467419, granted May 2011 [**S1**]. Via these **impact pathways**, Dixon and Smith established AE monitoring of landslides as a viable, lower cost, alternative to traditional methods. Since 2014, impacts have been achieved in three areas:

Impact 1: Improved public safety and infrastructure protection via affordable and increased landslide knowledge in UK, Italy and Canada was achieved by using our novel Slope ALARMS (SA) sensors to monitor stability of critical infrastructure (e.g., flood defences, roads, and properties), protecting people and delivering improved public service. SA sensors have been selected by infrastructure operators and used at sites with risk of landslides in the UK (five), Italy (two) and Canada (one). In all cases, data from the monitoring systems have been used by engineers and infrastructure owners to understand and manage risks and deliver public safety. Examples include:

a) Flood defence (UK) - The Environment Agency installed a SA system to monitor stability of a flood embankment on the Humber Estuary that uniquely is threatened by rapid erosion of a deep channel. The embankment protects 144 properties, businesses, and a cement plant. Monitoring was required to help protect the village while a new flood defence was being constructed. Warnings from the sensor were automatically sent to the Flood Incident Duty Officer and integrated into the South Ferriby Site Specific Procedures Manual [**S2**].

> "*Monitoring … was a complete success. It was the only affordable continuous monitoring solution with real-time warning capability that we could find. The significant benefit achieved was having confidence and peace of mind that the embankment was stable and capable of protecting those living and working in South Ferriby. While also knowing that we would receive an early warning if the embankment started to fail so that mitigation measures could be put in place to minimise the risk to residents.*" [**S2**]

b) Roads and property (UK) - SA sensors were installed in two unstable slopes in Monmouthshire that threaten local roads and a property, with warnings sent to the Council.

"*A key benefit of using Slope ALARMS was that sub-surface information could be obtained by retro fitting waveguides … hence installation would be rapid and costs would be very low.*" [**S3**] "*The most significant benefit of the monitoring is that I have been able to reassure the owners, at the site near Skenfrith, about the stability of the slope above their property ….*", "*This gives the owners peace of mind.*" [**S3**]

c) Coastal cliffs (UK) - Two slopes on the Yorkshire coast, near Filey and in Scarborough, have been monitored using SA sensors to help protect property and people.

"*The AE system provides the only continuous measurements of slope deformation behaviour available to us.*" [**S4**] *"…improves the reliability of our understanding of the problem and design recommendations …the scale and resolution of monitoring provided by Slope ALARMS was not previously available at an affordable price.*" [**S4**].

d) Road tunnels (Italy) – Five SA sensors were installed in a rock slope in Northern Italy that threatens the safety of two road tunnels that critically provide access for the local community and the 130,000 annual visitors to the region who rely on the tunnels.

"… the tunnels are the only way of accessing the village to/from the lower part of the valley, where many facilities, such as hospitals and industries, are located." [**S6**]. *"…based on our monitoring data, FVG Strade* [tunnel operator] *has decided to close the old road tunnel indefinitely due to the risk posed by the rock mass. This decision has been made according to … evidence of the monitoring data. The driving of my way of thinking has been the AE data.*" [**S5**]. *"… our community of 1500 people has benefited from the work that you have done to ensure our safety*" [**S6**].

e) Road (Canada) – Working with Thurber Engineering and Queen's University, Canada, a major road route into Peace River that is threatened by landslides has been monitored using Slope ALARMS to support decision making by Alberta Transportation.

Impact 2: Enhanced community resilience to landslides in Myanmar and Malaysia was achieved using our CSS early warning approach. Working with not-for-profit organisations, FHI 360 and CCERR committee for emergency response, we engaged with local communities to improve understanding and effective use of the CSS system. This delivered improved safety and understanding. In Hakha, the capital of Chin State, we established the first slope monitoring project in Myanmar to protect communities. We trained 20 Landslide Response Volunteer (LRV) youths, 60% female, recruited via a radio appeal to install, maintain and operate the CSS system. The LRV in turn acted as trainers for landslide awareness and CSS monitoring for 80+ people from the community [**S7**].

"*A critical benefit of the work in Hakha has been raising awareness in the community to help improve community resilience to future landslide events*"; "*I do not think that this would have been achieved without the research, technology and approach provided by LU. A unique impact of this collaboration on landslide monitoring was being able to align engagement of the central government of Myanmar all the way through the state government and CCERR agency to the youth volunteers and ultimately the community*"; "*In Myanmar, this project has been a catalyst for future landslide monitoring projects and has established the groundwork for government awareness and support*" [**S7**]; "*We estimate around 15000 – 20000 population in Hakha town benefits from the project.*" [**S8**]

A second community application of the CSS landslide monitoring system was delivered in Ampang District, Kuala Lumpur, Malaysia, working with community group SlopeWatch, Universiti Sains Malaysia, and the government slope agency. Installation, maintenance, and operation of the CSS system was delivered with the community. Two workshops attracting 40+ participants facilitated increased awareness and understanding of landslide risks, communicated the benefits of monitoring and provided a forum for community engagement with government agencies and politicians.

Impact 3: The world's first commercial, acoustic emission slope monitoring system, to deliver superior slope monitoring solutions, has been developed via a licensing agreement between LU and RST Instruments Ltd., a global geotechnical instrumentation company [**S9**, **S10**]. The *Geotechnical Instrumentation News* article generated discussion and resulted in LU entering into an agreement with RST, Canada and UK, in October 2017 for an exclusive world-wide licence to further develop, manufacture and distribute an AE slope monitoring system. Transfer of IP covered all technical information on Slope ALARMS [**R1** to **R5**] and Community Slope SAFE sensors [**R6**], plus LU associated knowhow on installation and operation of the AE slope monitoring systems. RST are a top five international geotechnical instrumentation specialist. With a global network of 22 distributors, sales result in an annual group turnover of ≈£29 Million [**S10**]. RST produce monitoring systems for applications in mining (e.g., tailings dams) and infrastructure (e.g., slopes) [**S9**]. Supported by Dixon and Smith, RST developed the world's first commercial AE sensors, Geo-Acoustic Aware (GAA), for slope monitoring. GAA was marketed globally in 2020 [**S9**].

> *"The business case for investing in development of … GAA sensor… was made by discussing the concept of the technology with a number of our high profile clients… The pull through revenue of having this unique product was also taken into account, generating additional sensors and increasing products sales across the board."* [**S10**]
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> *"RST… have invested considerable time, energy, and finance to develop, test and market the GAA sensor system. …this investment is over £200k and includes the creation of employment, as well as … benefits both within and to our supply chain."* [**S10**]
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> *"The addition of the product to the RST portfolio has added a unique value proposition… By allowing lower cost reliable measurement of slope stability we can provide a much more comprehensive monitoring solution… for no increase in budget. As no one else has this offering, interest in GAA has opened doors and generated conversations with new clients that otherwise would not have taken place".* [**S10**]

RST report that to November 2020, there has been significant interest in employing GAA from large global mining companies because GAA has been identified as filling a gap in current monitoring options (e.g., monitoring tailings dams). In addition, client discussions are on-going for monitoring rail slopes in Scandinavia and landslides in India, Myanmar, and Indonesia. GAA is being used to monitor slopes by a road authority in China. [**S10**]

> *"GAA forms an important part of RST's future strategy."* [**S10**]

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Apparatus and method for monitoring soil slope displacement rate by detecting acoustic emissions. UK patent GB 2467419 granted 18 May 2011, priority date 29 January 2009
S2. Catchment Engineer testimonial plus Environment Agency Flood Incident Duty Officer Procedures Document extract (2017 to 2019)
S3. Engineer testimonial, Highway & Flood Management, Monmouthshire County Council
S4. Geomorphologist testimonial, Jacobs, consultant for Scarborough Borough Council
S5. Testimonial, Research Institute for Hydro-Geological Hazard Protection, National Research Council of Italy, responsible for advising agencies on slope stability issues in Italy
S6. Mayor of Forni di Sotto testimonial, Passa della Morte, Northern Italy
S7. Chief of Party testimonial, FHI 360, Myanmar, a not-for-profit organization working to improve the health and well-being of people
S8. Testimonial from coordinator of Chin Committee for Emergency Response and Rehabilitation (CCERR), Hakha, Chin State, Myanmar
S9. RST Instruments GAA promotion materials (links to web pages and documents 2020)
S10. RST Instruments UK Managing Director testimonial.

Quotes corroborating impact in Section 4, are highlighted in each source document.