Institution:	**Loughborough University**
Unit of Assessment:	**B14 Civil and Construction Engineering**
Title of case study:	**A low-cost practical sensor for early warning of impending landslides in global environments**

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

Slope ALARMS is a novel low-cost sensor that detects acoustic emission and warns of the early signs of impending landslides. It has been developed and patented by Dixon at Loughborough University. British, Italian, Canadian and Austrian organizations with responsibility for vulnerable infrastructure have employed Slope ALARMS sensors since 2008 in locations with high landslide risk. Measurements have provided information on displacement rates and this is making a significant contribution to assessment of slope hazards. The invention has won awards and generated interest globally, raising public and professional awareness of landslide problems and the use of Slope ALARMS.

2. Underpinning research (indicative maximum 500 words)

World-wide, annually slope failures kill tens of thousands of people and damage infrastructure costing billions of pounds to repair. Research underpinning the impact reported here gave rise to the Slope ALARMS sensor – an instrument that warns of impending slope instability enabling people in harm's way to be evacuated and damage to critical infrastructure mitigated.

In studies at Loughborough University (LU) by Neil Dixon (1999 to present) a quantified link between acoustic emission (AE) from deforming soil and slope displacement rates has been established. This practical approach uses an 'active waveguide' installed in a slope. This novel device comprises a steel tube surrounded by granular backfill in a borehole passing through the shear surface, as shown in Figure 1. When soil movement strains the active waveguide, AE generated by the backfill is conducted by the tube to the surface, where it is detected and processed by the sensor. Research has shown that active waveguides are more sensitive than inclinometers, the standard approach.

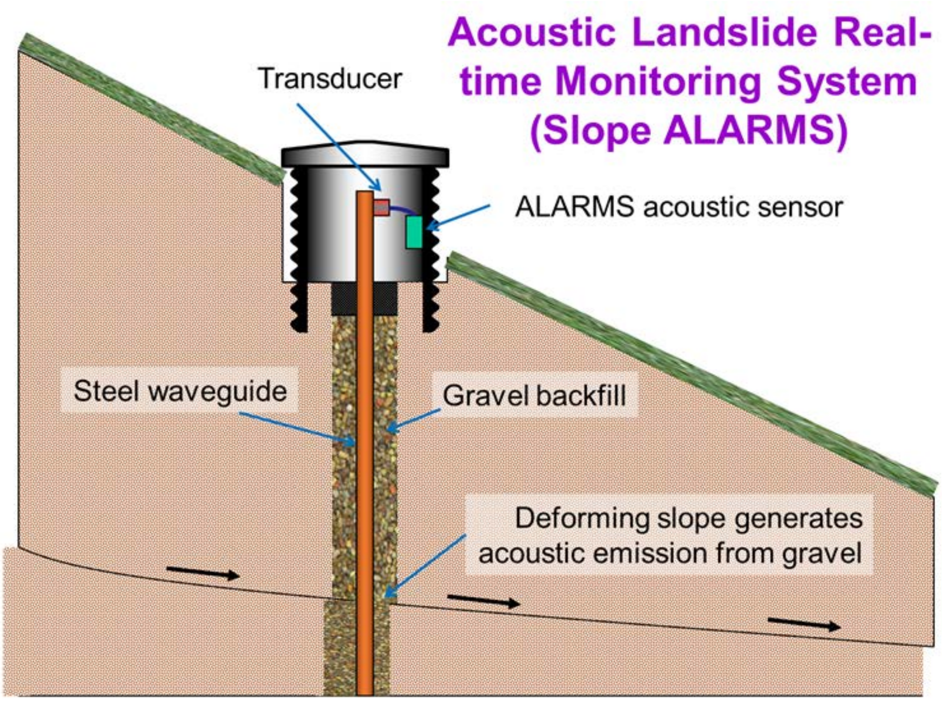

Figure 1: Slope ALARMS arrangement

In laboratory studies, 2000-2005, Dixon and PhD student Matthew Spriggs devised and then refined AE-processing techniques for characterising relationships between active waveguide generated AE rates and slope deformation rates. This was the first demonstration world-wide of AE monitoring capable of warning of instability and quantifying slope movement rates **[R1]**. In EPSRC-funded research **[G1]**, 2005, of a multi-sensor real-time AE monitoring system using active waveguides at the BIONICS research embankment (built to represent British transport embankments) a study demonstrated the technique is robust and not prone to false alarms.

Recognising the potential for the system to be used in routine monitoring, Dixon approached the British Geological Survey (BGS), which has expertise in developing field instrumentation, and proposed a research collaboration to produce the LU patented **[C1]** practical, unitary low-cost Slope ALARMS sensor capable of being installed and used anywhere in the world. With funding from EPSRC's Follow-on Fund **[G2]**, 2009, the partners designed and built sensors and trialled them on an active natural landslide over the 2009-10 winter **[R2]**. For the first time, the researchers were able to show clear correlations between signals from the AE sensors and inclinometer measurements of slope displacements. The research produced information on slope movements and demonstrated sensitivity of their AE sensors to rapid changes in displacement rate – a primary requirement for an early-warning system **[R3]**.

With funding from LU's EPSRC Knowledge Transfer Account (KTA) **[G3]**, 2010, Dixon had additional sensors produced to establish further trial sites. Monitoring of a large rock slope with road tunnel in the Alps, which is in danger of collapsing **[R4]**, has been in progress since 2010 with Italy's National Research Council, and at a railway-cutting landslide since 2011 with Network Rail and Geotechnical Observations Ltd. In 2011, finance from EPSRC's Collaboration Fund **[G4]** enabled re-engineering of the sensors with BGS to improve performance, and support from CH2M and Scarborough Borough Council made it possible for sensors to be employed in landslides at Flat Cliffs (2011) and Scarborough (2012) where slope movements cause distress to critical infrastructure. The sensors are a lower-cost monitoring option than traditional techniques.

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

Due to the imperative of obtaining a patent and engaging with potential users of Slope ALARMS, the strategy has been to delay publication of journal papers and present the field results at international conferences.

R1 Dixon, N. and Spriggs, M. (2007) "Quantification of slope displacement rates using acoustic emission monitoring", *Canadian Geotechnical Journal*, 44, 8, 966-976. DOI 10.1139/T07-046 (Peer-reviewed paper in one of the most highly rated journals in geotechnical engineering, which has a 5-year impact factor of 1.041)

R2 Dixon, N., Spriggs, M.P., Meldrum, P., Ogilvy, R., Haslam, E. & Chambers, J. (2010) "Development of a low cost acoustic emission early warning system for slope instability", in Williams, A.L., Pinches, G.M., Chin, C.Y., McMorran, T.J. & Massey, C.I. (Eds) *Proceedings 11th International Association of Engineering Geologists*, Taylor and Francis, Auckland, September, 1803-1810. (Peer-reviewed international conference paper)

R3 Dixon, N., Spriggs, M.P., Meldrum P. & Haslam, E. (2012) "Field trial of an acoustic emission early warning system for slope instability", in Eberhardt, E., Froese, C., Turner, A.K. & Leroueil, S. (Eds) *Proceedings of the 11th International and 2nd North American Symposium "Landslides and Engineered Slopes: Protecting Society through Improved Understanding"*. CRC Press, 2, 1399-1404. (Peer-reviewed paper in the leading international conference on landslides that is held every 4 years)

R4 Dixon, N., Spriggs, M.P., Marcato, G. & Pasuto, A. (2012) "Landslide hazard evaluation by means of several monitoring techniques, including an acoustic emission sensor", in Eberhardt, E., Froese, C., Turner, A.K. & S. (Eds) *Proceedings of the 11th International and 2nd North American Symposium "Landslides and Engineered Slopes: Protecting Society through Improved Understanding"*. CRC Press, 2, 1405-1411. (Peer-reviewed paper in the leading international conference on landslides that is held every 4 years)

Research Grants

G1 Dixon, *Assessment of Landslides using an Acoustic Real-time Monitoring System (ALARMS)*, EPSRC (EP/D035325), Dec 2005 – May 2009, £70,729

G2 Dixon, *Assessment of Landslides Using Acoustic Real-time Monitoring Systems (ALARMS): Low Cost Sensor Development and Exploitation*, EPSRC Follow-on Fund (EP/H007261), Aug 2009 – Jul 2010, £61,760

G3 Dixon, *Slope ALARMS: Proof of Concept*, EPSRC Knowledge Transfer Account, Sep 2010 – Aug 2011, £70,067

G4 Dixon, *Slope ALARMS: Sensor Technical Development*, EPSRC/Finance South East Collaboration Fund (EP/I502041), Feb 2011 – Apr 2012, £50,415

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

Dixon's research established the concept of active waveguides and demonstrated AE monitoring capability in the laboratory and through limited field trials. The initial system was complex, expensive, fragile, bulky and required mains power. It depended on expertise that only Dixon had, and even then, Dixon was only able to obtain slope-displacement measurements by post-processing data collected during site visits, so monitoring was not continuous or real-time.

With funding from EPSRC, including Follow-on, KTA and Collaboration Funds, Dixon and Spriggs have translated this apparatus into the Slope ALARMS sensor through the combination of research and knowledge-transfer work in collaboration with BGS. This is a patented, practical, low-cost, battery-powered unitary device with wireless communication of warnings. The sensor design has been developed to a level appropriate for manufacture, with the first batch produced in 2012. Validated in field trials, the sensor can be employed in slopes formed of a wide range of geological materials and configurations. It will continuously monitor and record AE generated by slope displacements and issue warnings of changing displacement rate by text message over a mobile-telephone network (www.slopealarms.com).

Dixon filed a UK patent application for an 'apparatus and method for monitoring soil slope displacement rate by detecting acoustic emissions' in January 2009. With support from LU's patent agent, this was revised and the application, naming Dixon and Spriggs as inventors, was successful. UK patent GB 2467419 was granted for the invention in May 2011 **[C1]**. A collaboration agreement between LU, proprietors of the patent, and BGS, developers of the electronic design, makes provision for apportioning income from commercialisation of the sensor technology.

The inventors entered Slope ALARMS in two competitions and won both. With Geotechnical Observations and BGS, they won the civil engineering category in *The Engineer* magazine's 2011 Technology and Innovation Awards, which *'celebrate collaborative engineering projects that have, or are likely to have, a significant impact on the sectors they are active in'* **[C2]**. It also won the commercialization category of LU's Enterprise Awards in 2010.

Beyond the two Slope ALARMS sensors operating at an experimental site since 2009 **[R2]**, there are now nine operating at sites in the UK, Italy and Canada at locations where landslides can do serious harm to infrastructure and local communities, with a further three installed in Austria in early 2014. Monitoring is in collaboration with CH2M **[C3]** at Scarborough promenade (since 2012) and Flat Cliffs (since 2011), Yorkshire, where coastal landslide movements threaten roads, water supply and use of public spaces, and in collaboration with Geotechnical Observations **[C4]** and Network Rail **[C5]** at a 12 metre deep rail cutting near Southampton (since 2011). In this application Network Rail are assessing whether Slope ALARMS can provide cost-effective real-time information to aid decisions about line safety. In the Italian Alps at Passo della Morte, there is a high risk of rapid movement within a complex of large landslides that threatens a critical road link. AE monitoring commenced in 2010 and four Slope ALARMS sensors are now in operation by Italy's Research Institute for Hydro-Geological Hazard Protection **[C6]** to understand the causes of slope displacements and warn of failure. Monitoring at these sites is aiding assessment of hazards and associated risks.

Slope ALARMS has attracted considerable media interest as a result of the publicity that followed the awards **[C2]**. Articles have been published in a national British newspaper **[C7]**, and in magazines published by professional societies **[C8]**, raising public and professional awareness of the device and the global problem of landslides.

International reach is demonstrated by on-going work to employ Slope ALARMS around the world. Slope ALARMS was installed in 2013 in a slope at Peace River, Alberta, Canada, that poses a risk to a main highway. This monitoring is in collaboration with Thurber Engineering and Queen's University, Canada. In 2013, Dixon in collaboration with German company INGLAS GmbH were awarded a contract by the Austrian Railway to install the *Sentinel for Alpine Railway Traffic* (SART) system to detect and warn of landslide hazards to alpine rail traffic. INGLAS conducted a review of landslide instrumentation systems world-wide and concluded that integration of Slope ALARMS in the SART system provides the optimum approach **[C9]** and three Slope ALARMS sensors will be installed in early 2014. Following several significant landslide events world-wide that have resulted in loss of life and damage to critical infrastructure, Dixon has been approached by companies and public organisations from more than ten countries regarding the use of Slope ALARMS as a viable technology for mitigating impacts of landslides.

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

The following sources of corroboration can be made available at request:

C1 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.

C2 'The Engineer Technology and Innovation Awards 2011' (2011, 12 December) The Engineer, pp. 33-42; also online at http://digital.centaur.co.uk/theengineer/te-121211/offline/download.pdf

C3 Letter of corroboration from Director of Geotechnics, CH2M, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE, providing details of the monitoring of coastal landslides threatening infrastructure and houses at Scarborough and Flat Cliffs in Yorkshire.

C4 Letter of corroboration from Managing Director, Geotechnical Observations Ltd, The Peter Vaughan Building, 9 Avro Way, Brooklands, Weybridge, Surrey KT13 0YF, explaining use of the sensor to monitor a cutting failure on the UK rail network.

C5 Letter of corroboration from Principle Geotechnical Engineer, Technical Services, Network Rail, Furzton Floor 3, Quadrant, Elder Gate, Milton Keynes, confirming details of the cutting slope failure monitoring and highlighting the benefits of this new approach

C6 Letter of corroboration from Director, C.N.R. - I.R.P.I., C.so Stati Uniti, 4, 35127 Padova, Italy, explaining use of the sensor to assess hazards on a complex of landslides in the Alps, including the benefits of the approach as part of an integrated monitoring and warning strategy.

C7 'The silent scream of soil on the slide.' (2010, 30 October) FT Magazine. http://www.ft.com/cms/s/2/eb4f6f88-e169-11df-90b7-00144feabdc0.html#axzz283NfnoPZ

C8 'Early warning systems "listens" for landslides.' (2010, December) Civil Engineering [American Society of Civil Engineers' (ASCE) magazine], p. 46–47.

C9 Letter of corroboration from Director, INGLAS GmbH & Co. Glärnischstr. 31/1, D-88045 Friedrichshafen, Germany, providing details of the selection process that led to incorporation of Slope ALARMS in the monitoring solution selected by the Austrian Railway.