Development of a low cost acoustic emission early warning system for slope instability

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ABSTRACT: Slope failures world-wide cause many thousands of deaths each year and damage built environment infrastructure. There is a clear need for low cost instrumentation that can provide an early warning of slope instability to enable evacuation of vulnerable people and timely repair and maintenance of critical infrastructure. Current instrumentation systems are either too expensive for wide scale use or have technical limitations. An approach, Assessment of Landslides using Acoustic Real-time Monitoring Systems (ALARMS), has been developed and demonstrated through research. An approach has been developed using measurement of acoustic emission generated during the onset of slope failure to provide quantitative information on slope displacement rates. Research is in progress to develop low cost acoustic sensors. A unitary acoustic emission slope displacement rate sensor has been designed and is being trialled in an active landslide. Continuous monitored acoustic emission rates show comparable trends to displacement rates measured using an inclinometer. Acoustic emission increase after rainfall events and this is considered to indicate increased displacement rates.

1 INTRODUCTION

Slope failures world-wide cause many thousands of deaths each year and damage built environment infrastructure, costing billions of pounds to repair, resulting in thousands of people being made homeless and the breakdown of basic services such as water supply and transport. The large majority of deaths from slope failures occur in developing countries located in tropical regions (e.g. South East Asia and Central America), triggered by extreme rainfall, and in earthquake prone regions. The United Nations International Strategy for Disaster Risk Reduction (UN-ISDR) through the Hyogo Framework for Action 2005-2015 Building the Resilience of Nations and Communities to Disasters (adopted at the UN Conference on Disaster Reduction, Japan 2005) has produced a five point action plan. The second element of this plan is *Identify, assess and monitor disaster risks and enhance early warning*. Specific gaps and challenges identified include the need to develop early warning systems whose warnings are timely and understandable to those at risk.

In developed countries, fatality rates are lower, however the impact on performance of infrastructure and cost of repair is high. In the UK, fatalities from slope failures are rare, but the current cost of unstable slope management is known to be considerable, although not quantified. Instability of both natural and constructed slopes presently has a significant impact on the built environment and infrastructure in the UK with many tens of thousands of people living with slope instability (e.g. Ventnor, Lyme Regis and parts of London and Edinburgh). Tens of thousands of kilometres of transport links and utilities are located in areas susceptible to failure of natural slopes. In addition, there are 20,000km of earthworks (i.e. cuttings and embankment) the failure of which has a major detrimental effect on the UK's infrastructure as demonstrated by the disruption of road and rail networks resulting from the many slope failures that occurred during periods of high precipitation in the last decade. There is growing concern that global change, in the form of climate change and increased population concentrated in urban areas, will result in a rise in the number and magnitude of slope failures causing fatalities, particularly in developing countries. In developed countries, climate change and the ageing infrastructure is anticipated to lead to increasing frequency of slope failures causing disruption to services and increased cost of maintenance (Dixon & Dijkstra 2007).

The need for low cost instrumentation that can be used to provide an early warning of slope instability to enable evacuation of vulnerable people and timely repair and maintenance of critical infrastructure is self evident. Current systems are either too expensive for wide scale use or have technical limitations. This paper details an approach based on acoustic emission real-time monitoring of soil slopes. It briefly summarises research to quantify acoustic emission generated by soil slope deformation, it outlines a monitoring system and research to develop low cost acoustic slope displacement rate sensors. Details of an ongoing field trial of the sensors is presented.

2 ACOUSTIC EMISSION MONITORING OF SOIL SLOPES

Materials undergoing deformation generate acoustic stress waves (also known as acoustic emission (AE) and sub-audible noise). Studies of acoustic emission aim to use the capture and measurement of the signal to determine the extent of material deformation. Examples of mechanisms that can generate AE are crack propagation in metals and concrete, and de-bonding between fibres and resins in composite materials. In soil, acoustic emission is generated from inter-particle friction and in rock by fracture propagation and displacement along discontinuities (*microseismic* and *rock noise)*. Acoustic emission can be detected using suitable transducers to provide information on the presence and location of straining.

Acoustic emission monitoring is not a new technique. It has been described in standard texts on geotechnical instrumentation (e.g. Dunnicliff 1988) and on landslide investigation (e.g. Schuster & Krizek 1978), although to date considerable scepticism exists regarding practicality of the technique. Stability of soil and rock slopes has been studied using AE techniques for over 50 years by international researchers. Although the low energy and high attenuation of AE in soil has hindered production of a viable field system. The most significant contribution in the area of acoustic emission behaviour of soil has been made by Koerner and his co-workers at Drexel University, Philadelphia, who carried out extensive laboratory and field studies of both fundamental AE characteristics of soil and field applications (e.g. Koerner *et al.* 1981). This work demonstrated that deforming soil produces detectable AE and that the levels of emissions are directly related to the stress state of the soil. More recently, a number of researchers in Japan have been active in acoustic emission research (e.g. Shiotani & Ohtsu 1999). This body of international research has demonstrated that acoustic emission is generated during soil slope movements and that AE monitoring is capable of detecting pre-failure deformations earlier than traditional instrumentation. However, interpretation of acoustic emission data was qualitative.

Dixon *et al.* (2003) and Dixon & Spriggs (2007) report research to develop a quantitative solution to this problem. Dixon *et al.* (2003) describe an approach using AE monitoring of active wave guides. Deformation of the soil body results in straining of the active wave guide system (steel tube with granular backfill surround) leading to generation of AE. Figure 1 shows a schematic of the measurement system. Initial field trials monitoring AE over discrete time periods demonstrated that slope deformations can be detected using active wave guides. In addition, AE monitoring detected pre-failure ground movements before traditional direct deformation measurements. However, monitoring was carried out over short time periods during site visits, data was post-processed in the laboratory and it was not possible to use AE rates to quantify displacement rates. Dixon & Spriggs (2007) detail an extensive laboratory investigation undertaken to develop AE processing and interpretation strategies that can be used to produce relationships between

AE and slope deformation rates. This research demonstrated for the first time that AE monitoring can be used to give both an early indication of slope instability and also quantification of slope movement rates. Quantification of AE is derived from calculating AE event/count rates and these can be related to rates of deformation for a given design of active wave guide. Figure 2 shows event rates measured in laboratory active wave guide deformation tests conducted at a range of displacement rates. Distinct and reproducible bands of results are obtained. AE event rates are directly related to displacement rates. Derived displacement rates are accurate to an order of magnitude, which is in line with current practice for classifying slope movements. The system is also sensitive to changes in displacement rate, making the technique suitable for detection of changes in relative slope stability in response to destabilising (e.g. climate related) and stabilising (e.g. remediation) events.

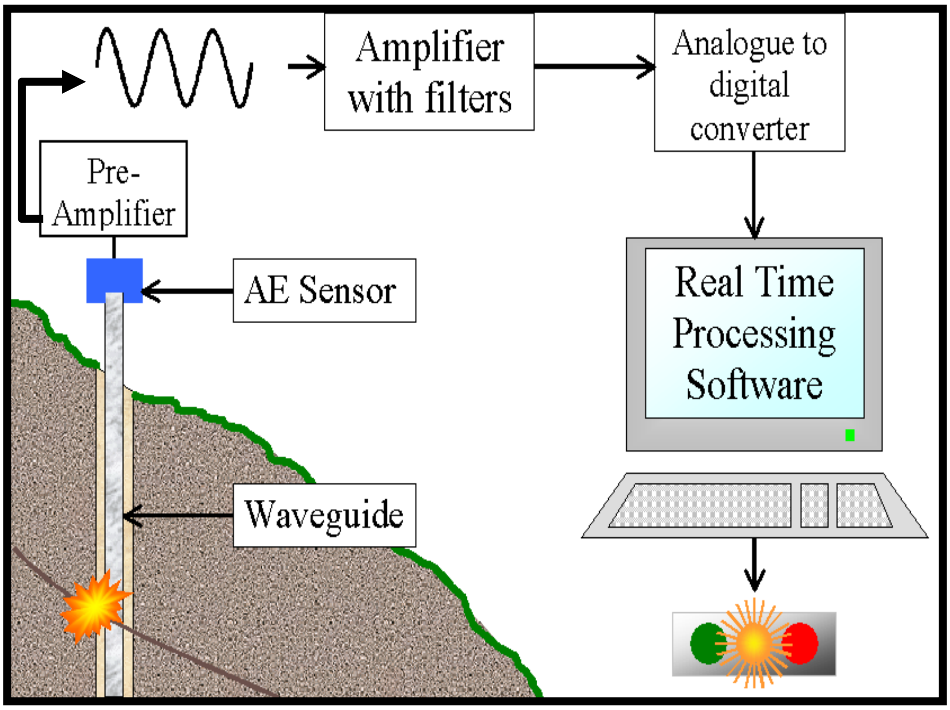

Figure 1. Schematic of the AE monitoring system, including active waveguide.

The monitoring strategy and instrumentation developed by Dixon & Spriggs (2007) has been trialled in the BIONICS test embankment (Hughes *et la.* 2009) through an UK Engineering and Physical Sciences Research Council (EPSRC) funded project ALARMS (Assessment of Landslides using an Acoustic Real-time Monitoring System). The ALARMS project trialled real-time AE soil slope monitoring instrumentation, with the aim of producing a rigorous practical early warning system. Nine active waveguides were installed in the slopes of the BIONICS embankment and AE continuous monitoring was carried out for periods up to several months at a time. Monitoring has demonstrated the robustness of the measuring system (i.e. minimal false alarms) and validation of performance is continuing through comparison of measured AE and displacement rates measured using inclinometers. The ALARMS system employs a multi-channel A to D board in conjunction with a PC for data processing, which allows central monitoring of all nine waveguides. However, this system is expensive, requires mains power, has multiple elements and needs a secure instrument hut.

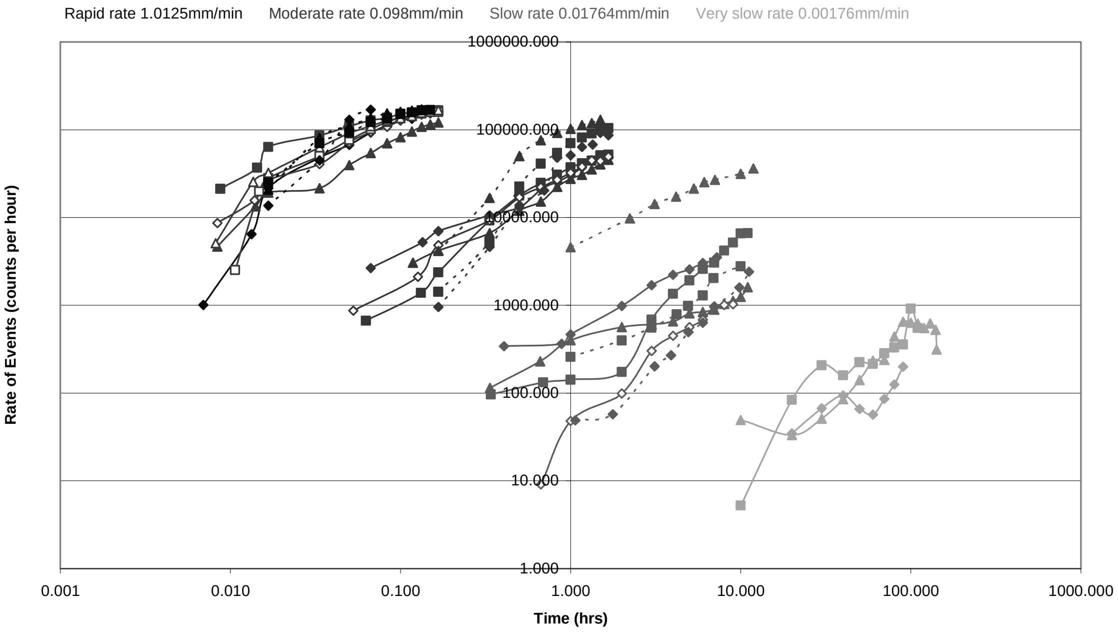

Figure 2. AE event rates for a range of active wave guide displacement rates (after Dixon & Spriggs 2007)

In order to make AE slope monitoring relevant for a range of applications and accessible to users in both developed and developing regions of the world, it became apparent that a simpler low cost system is required. A design for a unitary real-time acoustic emission soil slope displacement rate sensor has been produced by Dixon & Spriggs (2009). This comprises a piezoelectric transducer, a pre-amplifier, filters, an integrated signal processing, data storage and communication device, power supply and a secure, acoustically insulated chamber. The AE sensor is located on an active waveguide, which comprises a steel tube installed within in a granular material filled borehole constructed into a potentially unstable soil slope. The waveguide length can be many tens of metres long, with the length dictated by the need to intersect potential shear surfaces that may form beneath the slope. Acoustic emission are generated as the straining soil slope deforms the gravel backfill in the borehole and are transmitted to the ground surface by the steel waveguide. In real-time, generated AE are recorded at pre-defined time intervals and using a relationship between AE and displacement rates (i.e. an example is shown in Figure 2), derived through a laboratory calibration process, the AE rates provide quantitative information on slope displacement rates. The AE rates are recorded and compared to pre-determined trigger/action values based on both magnitude and changes in rate. If the trigger values are exceeded, an alert message that includes the measured displacement rates is communicated to a nominated person(s) to enable relevant action to be taken. A collaborative research project, ALARMS Low Cost, funded by EPSRC between Loughborough University and British Geological Survey is currently in progress to design, build and trial these unitary AE sensors.

3 FIELD TRIAL OF AE SENSOR

3.1 *Introduction*

In order for any new instrumentation to be accepted by users there is a need to compare performance against traditional well established techniques, which for slope monitoring is inclinometer based systems. This is required to demonstrate the AE instrument is robust and can operate in the field environment (i.e. temperature and humidity ranges), that it is capable of detecting deformation rates commonly measured using inclinometers and that there are benefits in using the new AE technique, such as improved performance (i.e. sensitivity) and reduced cost. A slope early warning system should provide sufficient warning to enable action to be taken (i.e. implement an emergency plan), it must be robust so that false alarms are not generated as this undermines confidence and also provide information on rates and magnitude of movement so that likelihood and significance of failure events can be determined. In addition, it should allow the mode of failure to be identified so that the significance of a failure event can be assessed. A field trial is currently in progress to compare unitary AE sensor performance against inclinometer measurements. An active landslide at Hollin Hill (Figure 3) was selected for the trial as in recent years slope deformations have occur during the winter months and there was confidence that measurable slope deformations would be experienced during the period December 2009 to April 2010. The British Geological Survey has developed and installed at this site a permanent geophysical and geotechnical monitoring system to assess the suitability of resistivity and self-potential (SP) methods for investigating and monitoring spatial and temporal behaviour (Chambers *et al.* 2008).

3.2 *Hollin Hill site geology and hydrogeology*

The Hollin Hill research site [SE 6807 6883] lies 11 km to the west of Malton, North Yorkshire, UK, occupying an elevation of between 55 and 100 mAOD. The site is located on a south facing valley side with a slope of approximately 12^{o}. The bedrock geology, from the base to top of slope, comprises the Lias Group Redcar Mudstone Formation (RMF), Staithes Sandstone and Cleveland Ironstone Formation (SSF), and Whitby Mudstone Formation (WMF), which are overlain at the top of the hill by the Dogger Sandstone Formation (DF). The bedrock is relatively flat lying with a gentle dip to the north. Slope failure at the site is occurring in the weathered WMF, which is highly prone to landsliding. The landslide is characterized by shallow rotational failures at the top of the slope that feed into larger-scale slowly moving lobes of slumped material (Figure 3); the rotational features and active lobes extend approximately 150 m down the slope from the top of the hill, and extend laterally more than 1 km along the valley side. In recent years, movement of the lobes has been in the order of tens of centimetres per annum. Movement typically occurs in the winter months (i.e. January and February) when the slope is at its wettest. During this period water can be observed accumulating in the basins caused by rotational slips towards the top of the slope, and can be seen emerging from the front of the lobes. Drainage from the site also occurs along a spring line at the base of the SSF, where groundwater appears to be running off the surface of the less permeable underlying RMF. Recently installed piezometers have revealed elevated pore pressures at the failure planes within the slipped WMF and at the interface between the slipped WMF material and the underlying SSF.

3.3 *Installation of AE waveguides and inclinometer casings*

Three pairs of active waveguides and inclinometer casings have been installed through two of the lobes (Figure 3). The waveguides were installed in 130mm diameter holes to depths of 5.7 m below ground level. The waveguides comprise two 3.0 metre lengths of 50 mm diameter 3mm thick steel tubing connected with screw threaded couplings. The annulus around the steel tubing, which is located in the centre of the borehole, is backfilled with angular 5 to 10 mm gravel. This is placed in nominally 0.25 metre high lifts, each compacted before addition of the next lift. The top 0.3 metres of the borehole is backfilled with a bentonite grout plug to seal against the ingress of surface water. The steel tube extends 0.3 metres above ground level and is encased in a secure protective chamber (Figure 4). Inclinometer casings were installed approximately 1.0 metre from the wave guides in a direction perpendicular to the slope. The inclinometer casings penetrate to a depth of 6 metres below ground level and the annulus around the casing is grouted using medium stiffness cement bentonite grout. Secure covers are constructed over each casing.

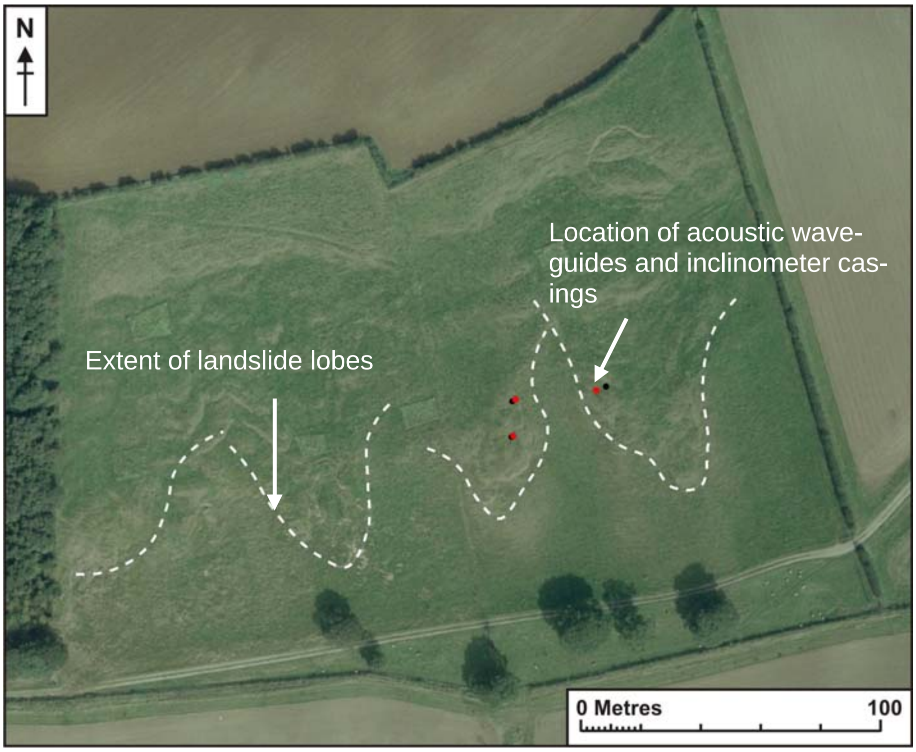

Figure 3. Aerial photograph of the Hollin Hill research site with the extend of the landslide lobes defined and the waveguides/inclinometer instrument locations marked (© UKP/Getmapping Licence No. UKP2008/01)

Figure 4. Acoustic waveguide with protective cover and adjacent inclinometer casing

3.4 *AE sensor*

A unitary AE sensor is located inside the protective cover. A piezoelectric transducer is attached to the waveguide and linked to the sensor via a cable. The AE sensor is powered by a battery, which is re-charged by a solar panel (Figure 4). Monitoring is continuous. Cumulative AE ring down counts are recorded and time stamped for each 15 minute period. Monitoring commenced on 15th December 2009 and is ongoing. Initially, the data is being downloaded from the sensor manually during weekly site visits to read the inclinometer casings. However, wireless communication units are being added to the sensors to enable remote real-time access to the AE data.

3.5 *Preliminary results*

The landslide lobes are deforming on shear planes located 1 to 2 metres below ground level. AE has been monitored continuously during the period 15th December 2009 to 3rd February 2010, except for 11th to 19th January when battery failure resulted in loss of information. The adjacent inclinometer casing has been surveyed on 6 occasions during this period including the first and last date for which there is AE data presented. The inclinometer readings indicate that the landslide is moving at rates in the range 0.02 to 0.27 mm per day and hence would be classified as very slow. Figure 5 shows the cumulative AE where it is compared to cumulative displacements over the same period. Also show are rainfall records.

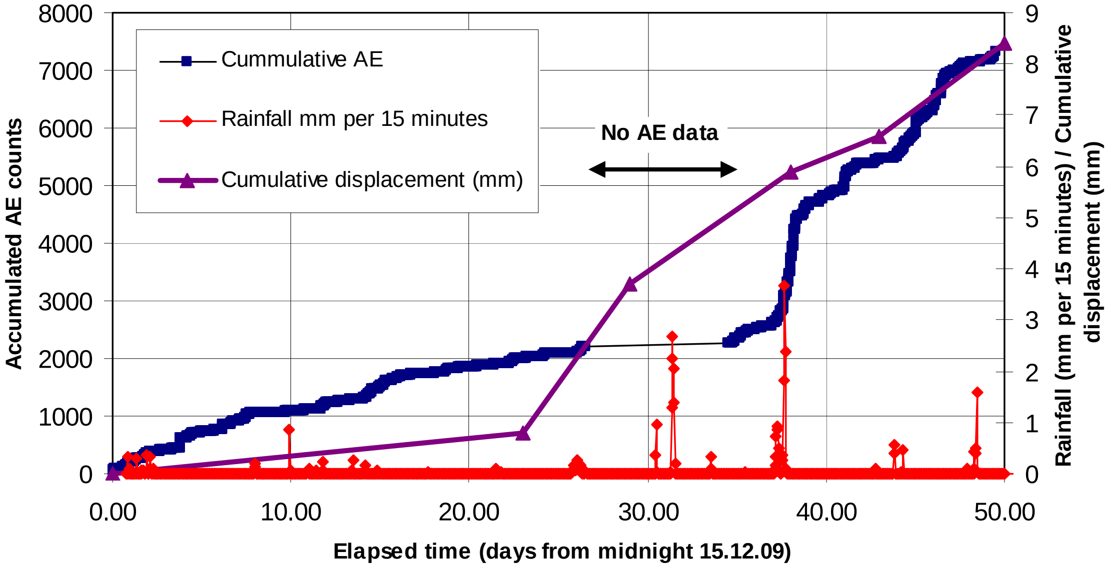

Figure 5. Preliminary cumulative AE data compared to cumulative displacement and rainfall

Of note is that there is a correlation between AE and displacement rates. The slopes of both the AE and displacement vs. time plots increase after 29 days, demonstrating that the increased displacement rate is indicated by the AE measurements. The increase in displacement rate is believed to be in response to rainfall events, however, as the displacement data has not been monitored in real time, the direct relationship has not been observed. This also means that it is not possible to compare directly the timing of changes in displacement and AE rates, which is further complicated by the period of missing AE data. However, there is a very clear relationship between increased AE and rainfall (e.g. days 37/38), which is interpreted as indicating an increase in displacement rate. It should be noted that the slope was covered in snow during part of the monitoring period (approximately days 20 to 30) and that the rainfall measurements are unlikely to include this element of precipitation. The results presented in this paper are preliminary and analysis of trends is still ongoing. By the end of the 2009/10 winter period, data will have been collected from all three waveguides with real-time monitoring over extended periods of time. It will then be possible to provide more detailed analysis and conclusions. These initial measurements are however very promising.

4 SUMMARY

The paper introduces the concept of using acoustic emission monitoring to assess stability of soil slopes. International research over the past 50 years has demonstrated that deforming soil slopes generate detectable AE and that rates of AE are proportional to displacement rates. Previous research by the Authors has developed a monitoring system using active waveguides and an associated processing procedure that employs quantified AE rates to measure slope displacement rates. Design of a unitary AE sensor is detailed in the paper. This is a relatively low cost real-time slope monitoring system. The AE sensor is being trialled on an active landslide at Hollin Hill, North Yorkshire, UK, where performance is being compared to traditional inclinometer slope displacement measurements. Preliminary results indicate that there is a direct relationship between AE and displacements. Increased AE rates following rainfall events are considered to indicate increased slope displacement rates. The field trial of AE sensors is ongoing and a more detailed interpretation will be possible at the end of the 2009/10 winter period.

5 ACKNOWLEDGEMENTS

We would like extend our sincerest gratitude to Steve and Josie Gibson (the Hollin Hill landowners) for their involvement and cooperation in the research. This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

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