Institution: Keele University

Unit of Assessment: B7 Earth Systems and Environmental Sciences

Title of case study: Microseismic Monitoring for Environmental Applications

1. Summary of the impact

Keele University has a forty year history in the theory, development and application of microseismic (small-magnitude 'earthquakes') monitoring and characterisation methods for the investigation of geotechnical, geological and geo-environmental problems, which continues to form a key aspect of its environmental and sustainability agenda, one of Keele's overarching strategic priorities.

Since 1993, Professors Young & Styles' research at Keele (the Applied and Environmental Geophysics Group) has led to new international standards in the monitoring of ground deformation and fracturing associated with underground mining (coal, salt, gypsum), coal-bed methane extraction, high-level nuclear waste disposal and, most recently, the emission of low-frequency vibrational noise from wind turbines and the exploitation of shale gas hydrocarbon reserves.

Keele's research has been instrumental in developing new hardware, software, data acquisition, processing and visualisation technologies that are now considered *de facto* across the international microseismic monitoring community (both industrial and academic). Keele's research work has contributed to the significant development of new, UK on-shore gas reserves and the de-regulating of Ministry of Defence (MOD) land for long-term renewable energy development.

2. Underpinning research

Microseismic monitoring is the detection, location and characterisation of low amplitude earthquakes generated by small-scale movements in the sub-surface. These can be natural (i.e. the movement of active geological faults) or man-made (e.g. the collapse of abandoned seams in coal mines). Generally, these low amplitude earthquake events are only detectable by sophisticated seismic monitoring systems, although their impact can be severe (e.g. local subsidence, ground water flow disruption, etc.). Microseismic mointoring allows researchers to assess the location and time-dependent nature of these events (e.g. where and how subsidence will occur) therefore providing predictions for risk management and mitigation strategies.

The monitoring techniques developed at Keele are able to detect the smallest underground microseismic events (a very complex and difficult task) and the research has found relevance across the wider sector of environmental engineering (e.g. wind farm turbine monitoring, development and exploitation of new on-shore gas reserves) and geological/geotechnical engineering (e.g. coal and salt mining collapse).

From 1993-2000, Microseismic research at Keele was led by Professor Paul Young (Chair of Applied Seismology) where many of the commercial microseismic processing and monitoring techniques used today in the mining and geotechnical engineering industries were pioneered**.** Professor Young is currently the Vice-President (Research) at the University of Toronto, Canada and Keck Chair of Seismology and Rock Mechanics. In 2000, Professor Peter Styles joined Keele as Chair of Applied and Environmental Geophysics, continuing the theme of applied microseismics research. Professor Styles has been at the forefront of international high-resolution microseismic data processing and monitoring research for over thirty years. He is the Past-President of the Geological Society of London, a Board Member of the British Geological Survey and Geophysical Advisor to the Coal Authority.

Research within the current Applied and Environmental Geophysics Group is focused around the engineering/technical development of hardware, software, methodological approaches, fundamental theory, data processing, numerical/mathematical modelling and data interpretation/visualisation methods for the monitoring, evaluation and characterisation of these microseismic signals, predominantly in the mining and energy sector. The research is practical and applied in nature, and has been funded by UK research councils (NERC, EPSRC), The Royal Society, EU, UK and

international industry (e.g. National Grid Carbon, Wind Energy (Newfield), Proven Energy, Reactec) national Government agencies (DTI, DECC), the Ministry of Defence and regional and local government (e.g. Advantage West Midlands, Vale Royal Borough Council, £600k).

3. References to the research

Pringle JK, Styles P, Howell CP, Branston MW, Furner, R, and Toon SM. (2013). Long term time-lapse microgravity and geotechnical monitoring of relict salt-mines, Marston, Cheshire, UK, *Geophysics* **77**(6): B287-B294. doi:10.1190/geo2011-0491.1

Manly DMJP, Styles P, and Scott J. (2002). Perceptions of the public of low frequency noise. Journal of Low Frequency Noise, *Vibration and Control* **21**(1):37-44.

Rushforth I, Moorhouse A, Styles P. (2002). A case study of low frequency noise assessed using DIN 45680 criteria, *Journal of Low Frequency Noise and Vibration* **21**(4):181-198.

Young RP, Hazzard JF, Pettitt WS. (2000). Seismic and micromechanical studies of rock fracture, *Geophysical Research Letters* **27**(12):1767-1770.

Hazzard JF, Young RP, Maxwell SC. (2000). Micromechanical modelling of cracking and failure in brittle rocks, *Journal of Geophysical Research* **105**:16683-16,697.

Green CA, Styles P, Baptie JP. (2012). Preese Hall Shale gas fracturing, review & recommendations for induced seismic mitigation. Report to the Department of Energy and Climate change, pp. 26. http://og.decc.gov.uk/assets/og/ep/onshore/5075-preese-hall-shale-gas-fracturing-review.pdf

Styles P. (2010). An assessment of the REACTEC/Wind Energy damping system for the reduction of ground vibration in the 3 to 6 Hz band and the implications for Eskdalemuir IMS seismometer array station", Report to the Scottish Government, Department of Planning and Appeals. www.dpea.scotland.gov.uk/Documents/qj12573/j165206.pdf

Styles P, Stimpson IG, Toon SM, England RJ, Wright M. (2005). Microseismic and infrasound monitoring of low frequency noise and vibrations from windfarms: Recommendations on the Siting of Windfarms in the Vicinity of Eskdalemuir, Scotland. Report to MOD/DTI/BWEA, July 2005, pp 125.

Vella G, Rushforth I, Mason E, Hough A, England RJ, Styles P, Holt T, Thorne P. (2001). Assessment of the effects of noise and vibration from offshore windfarms on marine wildlife. Department of Trade and Industry, Energy Technology Support Unit (DTI/ETSU) report w/13/00566/REP

Styles P, Toon SM, Bryan-Jones A. (1996). Microseismic monitoring work in the vicinity of Asfordby Colliery including the seismic mapping of the location of mechanical failures in the Overburden: Research Contract 2069/3 (International Mining Consultants). 116 p.

4. Details of the impact

From 1993-1998 Keele researchers were awarded grants from the Atomic Energy of Canada Ltd (AECL) Underground Research Laboratory (~£1 million) for the "Application of Induced Seismicity to Radioactive Waste Management Programmes". At this time, Applied Seismology Consultants Ltd. (ASC) was formed around the research strengths of Keele's Applied Geophysics Research Group **[1]**. ASC is now part of Itasca International **[2]**, a world-leading microseismic/geotechnical engineering company. Keele-based research has improved our understanding of rock fracturing/seismicity around the construction of nuclear repository tunnels and its influence on the development of fluid flow around radioactive waste materials. The research has underpinned the fundamental design of all underground repositories, and impacted on the selection/mode of nuclear disposal internationally. The techniques/software developed during these Keele-based projects (e.g. InsiteTM) are now routinely used by international companies associated with the construction, monitoring and disposal of nuclear waste underground (e.g. SKB Sweden; INERIS, ANDRA & ENS France) **[1]**.

Professor Styles (Chair of Applied and Environmental Geophysics) was the first to show the importance of microseismic monitoring for the prediction of coal-face outbursts, a world-wide problem in anthracite mines. He has advised the Australian and Canadian Mining Industry on how to combat

these problems using microseismic techniques, with Australian monitoring of coal mines now based on research he initiated and developed at Keele **[3]**. In 2009, Professor Styles was a member of the Foreign Office Clean Coal Technologies Mission to Australia as scientific advisor to the national coal industry on the development (and hazard implications) of developing Coal Bed Methane (CBM) energy. In the UK, the Outburst Prediction system developed by the group was deemed by HM Inspector of Mines to be a mandatory requirement for mines in the UK, which laid the foundation for new mine-stability monitoring technologies in the salt/gypsum industries. In 2002, Keele was awarded a £600k grant from Vale Royal Council for the Microseismic Monitoring of Salt Mine Instability in Northwich, Cheshire (2002-2007). The research provided vital information on the stability and deformation characteristics of ground above and surrounding the mines, and was pivotal in the design and ongoing monitoring of English Partnership's £32 million remediation programme (funded from the Government's Land Stabilisation fund). The stabilisation of the mines led to the establishment of the 2007+ "Northwich Vision" regeneration programme and the comprehensive Northwich Urban Design & Public Realm Strategy of 2010 **[4]**.

Keele-based microseismic research has led to staff serving on (and Chairing) a number of key government policy-making advisory groups including

- DEFRA/DTI Criteria Proposals Group (CPG), Sub-Surface Exclusion Criteria for Geological Disposal of Radioactive Waste (MRWS), 2006-7.
- NDA Geosphere Characterisation Panel (2008-),
- Royal Society Committee on Non-Proliferation of Nuclear Weapons (2010-).
- President of the International Commission on Hydrocarbon Exploration and Seismicity in the Emilia region, Italy (2013-)

In 2011, the Department of Energy and Climate Change invited Prof. Styles to join the independent evaluation panel investigating the implications/nature of microseismicity associated with "Shale Gas Hydraulic Fracturing" in Lancashire. Their 2012 report "Preese Hall Shale Gas fracturing, Review & Recommendations for induced seismic mitigation" has been pivotal in the government's decision to resume UK Shale Gas exploitation on the basis of low microseimic risk. Key recommendations of the report were that future shale gas operations should include...*"seismic monitoring to establish background seismicity"* and an *"effective monitoring system that can provide automatic locations and magnitudes of any seismic events in near real-time"* **[5]**. The research undertaken at Keele in the past fifteen years has underpinned the development of these techniques and the methodologies needed to meet the report's recommendations **[6]**. This work has led to Keele's involvement in the recently formed "ReFINE Consortium" (Researching Fracking in Europe with Durham, Newcastle and Heriot-Watt as University partners) funded by RCUK and industry.

Keele has been instrumental in developing our understanding of the nature, magnitude, risk and implications of ground vibrations from onshore wind turbines. In 2004-6, the group was funded by the MOD to undertake a £115k programme of research at Eskdalemuir, Scotland. The project assessed the impact of turbine-related microseismic noise on the MOD's nuclear test ban treaty seismometer network and showed that, within certain distance limits, wind turbines have little influence on the network's detection capability or human health (as presented in a 2011 House of Lords debate **[7]**). Keele-based work has had a major, positive impact on the development of the UK's onshore wind provision and led directly to the permission for, and construction of, 1.5 GW of renewable wind energy in the Southern Uplands of Scotland, equivalent to inward investment of £1.5 billion. This research has been highly commended by the Ministers of State for Energy & Defence **[8]**, and has helped the UK government meet its commitment to the Kyoto CO_2 emission reduction targets (through renewable energy provision). The outcomes of Keele's research have also been integrated into the 2006 US "Report To The Congressional Defence Committees on The Effect of Windmill Farms On Military Readiness" along with the recommendation that the Keele-developed monitoring methodologies be adopted for all US wind farm sites **[9]**. This work also has implications for the monitoring of offshore Carbon Capture and Storage (CCS) in the presence of an extensive network of offshore wind-farms, with current research being funded by DECC and NGC (Nanjing High Speed Gear Manufacturing Co).

5. Sources to corroborate the impact

[1] Applied Seismology Consultants "Microseismic Monitoring of the Engineered Environment" software Insite™

http://www.seismology.org/software/packages

[2] ITASCA International - http://www.itascacg.com/

[3] Styles P, Bishop I, Toon S. (1997). Surface and borehole microseismic monitoring of mining-induced seismicity, in McCann DM, Eddleston M, Fenning PJ. Reeves GM. (eds) Modern Geophysics in Engineering Geology, Geological Society, London, Engineering Geology Special Publications 1997, v. 12, p. 315-326, DoI 10.1144/GSL.ENG.1997.012.01.29

[4] Cheshire West and Cheshire, Northwich Urban Design & Public Realm Strategy (page 9) http://northwichriverside.co.uk/wp-content/uploads/2013/07/Northwich-UDGPR-FINAL-ISSUED-VERSION-22-11-10.pdf

[5] Executive Summary from report "Preese Hall Shale gas fracturing, review & recommendations for induced seismic mitigation. Report to the Department of Energy and Climate change" pi-iii. https://www.gov.uk/government/publications/preese-hall-shale-gas-fracturing-review-and-recommendations-for-induced-seismic-mitigation

[6] Davies R, Foulger G, Bindley A, Styles P. (2013). Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology*. **45**:171-185. DOI:10.1016/j.marpetgeo.2013.03.016

[7] House of Lords debate: 18 Oct 2011: Column WA51. http://www.publications.parliament.uk/pa/ld201011/ldhansrd/text/111018w0001.htm#11101860000050

Lord Marland (Parliamentary Under Secretary of State, Energy and Climate)

"A comprehensive study of vibration measurements in the vicinity of a modem wind farm was undertaken in the UK in 1997 by ETSU for the Department of Trade and Industry (ETSU W/13/00392/REP). The report found no evidence that ground transmitted low frequency noise from wind turbines is at a sufficient level to be harmful to human health. These findings were confirmed by a study published in 2005 by the Applied and Environmental Geophysics Group of the School of Physical and Geographical Sciences at Keele University titled Microseismic and Infrasound Monitoring of Low Frequency Noise and Vibrations from Windfarms."

[8] Letter from Parliamentary Under Secretary of State, Ministry of Defence, Minister of State for Energy, Department of Trade and Industry, and Chief Executive, British Wind Energy Association.

[9] "Report To The Congressional Defense Committees on The Effect of Windmill Farms On Military Readiness" 2006. Office of the Director of Defense Research and Engineering, Dept of Defense, United States. http://www.defense.gov/pubs/pdfs/windfarmreport.pdf