Institution: Durham University

Unit of Assessment: 17

Title of case study: The management of landslides and rockfalls

1. Summary of the impact

A long-term research programme into landslides and rockfalls by DU researchers, focused on the use of novel field and laboratory techniques, has had impact on UK and foreign government authorities, NGOs, and businesses. The work has provided frameworks for managing hazard associated with deep-seated landslides in New Zealand and a landslide-dammed lake in northern Pakistan. Research on coastal cliff erosion in North Yorkshire has provided critical support for high-value mining activities at the UK's largest non-hydrocarbon extractive mine, and has underpinned local government strategies for shoreline hazard assessment and management.

2. Underpinning research

The ability to forecast landslides and rock avalanches is the biggest challenge in slope stability research. DU Geography researchers Petley (DU staff 2000-), Rosser (PDRA 2002-7, RCUK Fellow 2007-12, Lecturer 2012-), Dunning (PDRA 2004-8), Lim (PhD 2002-6, PDRA 2007-10), Carey (PhD 2003-2011), Higuchi (PDRA 2000-2005) and Massey (PhD 2003-2010), have addressed this problem from two complementary perspectives, showing that different types of landslide have quantifiably different patterns of acceleration before failure (References 1 & 2), and thus that monitoring very small-scale precursory movements offers the prospect of forecasting a landslide or rock avalanche. The novelty of our approach is in the development of pioneering laboratory and field-based techniques to assess hazards associated with rock slopes, soil slopes, and unstable natural dams (References 3-6).

Laboratory testing: DU research has led to the development of new laboratory equipment that is capable of simulating conditions within landslides more realistically than has previously been possible. This equipment has permitted investigation of how geology and failure mechanism influence landslide behaviour immediately before slope collapse (Reference 1). Laboratory work has focused on defining how such pre-failure behaviour is controlled by groundwater pressure and the progressive loss of material strength through time (Reference 2). Constraining this behaviour is important because it allows us to establish the ways in which hillslope material deforms immediately before a landslide occurs, and thus provides testable predictions about the kinds of precursory movements that could be observed in the field. This research was enabled by collaboration with GDS Instruments Ltd, a UK-based SME, who designed and built new back-pressured direct shear cells to our specification. Uniquely, these laboratory cells allow real-world groundwater pressure and shear strain conditions to be controlled. The cells enabled us to establish the micromechanical controls on first-time landslide failure and to forecast the conditions under which landslides behave as either catastrophic/brittle (high risk) or slow/ductile (low risk), based upon material stress-strain behaviour alone.

Novel field-based monitoring and modelling: Motivated by the movement patterns predicted by laboratory simulations (References 1 & 2), a second area of DU research has focused on the ability to predict landslides and rockfalls based on the capture, interpretation and forecasting of small-scale pre-collapse movements and the evolution of failed material. This work has followed three separate strands related to reactivated (deep-seated) landslides, rock avalanche deposits, and rockfalls:

(1) Detailed analysis of a reactivated landslide in New Zealand led to a framework for using monitoring data – in this case, surface displacements derived from continuous GPS measurements – to identify the mechanisms responsible for landslide movement, and showed a complex link between rainfall and landslide movement (Reference 3).

(2) A second strand of work has investigated the sedimentology and evolution of large rock-avalanche deposits. Such deposits often dam rivers in mountain valleys, creating lakes that can unleash catastrophic floods if the dam fails. By modelling seepage and pore water pressure, we

have shown that the stability of such dams is sensitive to the grain size and structure of the material, and that failure may occur within days to weeks of lake filling (Reference 4).

(3) We developed a now widely-used protocol to extract detailed 3D models of rockfalls using repeat terrestrial laser scanning, and have used this approach to identify characteristic patterns of pre-collapse movement in coastal cliffs and other settings. This work has enabled unprecedented resolution in monitoring rock cliff erosion rates, allowing quantitative rockfall risk assessment and providing the first insights into the mechanics that control rockfall timing (References 5 & 6).

3. References to the research (**Bold** denotes Durham University staff at time of research, underline denotes DU research student. Journal impact factors and citations are from Web of Science as of 31/7/2013.)

1. **Petley** DN, Bulmer MH, Murphy W (2002) Patterns of movement in rotational and translational landslides. *Geology* 30,719–722. (JIF 4.09, 36 citations)
2. **Petley** DN, **Higuchi** T, Petley DJ, Bulmer MH & Carey J (2005) Development of progressive landslide failure in cohesive materials. *Geology* 33,201-204. (JIF 4.09, 34 citations)
3. Massey CI, **Petley** DN, McSaveney MJ (2013) Patterns of movement in reactivated landslides. *Engineering Geology* 159, 1-13. (JIF 1.40, 0 citations).
4. **Dunning** SA, Armitage PJ (2011) The grain-size distribution of rock-avalanche deposits: implications for natural dam stability. In: Evans SG, Hermanns RL, Strom AL, Mugnozza S. (Eds.), NATO Science Series: IV Earth and Environmental Sciences - Natural and Artificial Rockslide Dams (NATO Advanced Research Workshop, Bishkek 2005); Springer, Dordrecht, Chapter 8. (2 citations). NB this work was carried out in 2005-2006, but delays in publication mean that the paper was published after Dunning left DU.
5. **Rosser** N**, Lim** M**, Petley** D**, Dunning** S**, Allison** R (2007) Patterns of precursory rockfall prior to slope failure. *J. Geophysical Research – Earth Surface* 112, F04014 (JIF 3.17, 17 citations)
6. **Rosser** NJ**, Petley** DN**, Lim** M**, Dunning** SA**, Allison** RJ (2005) Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Quarterly Journal of Engineering Geology & Hydrogeology* 38, 363-375. (JIF 0.76, 68 citations)

4. Details of the impact

The impact of DU research into landslides and rockfalls has been achieved via two distinct pathways. In the first, laboratory-derived understanding of landslide behaviour has led to better quantitative interpretation of field data and to the design and installation of landslide early-warning systems in New Zealand, while in the second, our monitoring techniques have allowed ongoing and near-real time management of landslides and landslide-prone areas.

1. From laboratory to forecasting: landslide management and early warning

Our laboratory research on landslide behaviour has improved early warning systems by providing a better understanding of failure mechanisms. The bespoke instrumentation developed in collaboration with GDS Instruments Ltd was used to provide the first proper behavioural forecasting of large landslides and is now sold commercially by GDS, who state that the instruments were “developed in conjunction with the University of Durham” (Source 1).

A key example of the direct application of landslide behaviour research for early warning is our collaboration with GNS Science, the New Zealand government hazards research agency. DU research on landslide failure mechanisms in the laboratory (Reference 2) and observations of the patterns of precursory motion on the ground (Reference 3) allow GNS Science to interpret landslide surface movement data in terms of the material stress-strain behaviour, enabling a quantitative and process-based assessment of risk (Source 2). As a direct impact of this research, GNS Science has installed movement and early warning systems in large landslides at Taihape (in operation from 2007-2011) and Utiku (2007-present) on New Zealand’s North Island. These landslides were chosen as exemplars of more than 7,000 similar landslides with areas of >10,000 m^2 that occur in Neogene rocks across New Zealand (Source 2). The landslide at Taihape underlies much of the town, while that at Utiku underlies State Highway 1 and the North Island Main Trunk railway line, which links New Zealand’s capital (Wellington) with its largest city (Auckland) and is the central target of a NZ$4.2bn ‘turnaround plan’ (2010-2020). Source 2 states that “GNS Science used the techniques and approach articulated in two papers authored by

Professor Petley [References 1-2] as the basis for the methodology used to develop the monitoring networks installed on the Taihape and Utiku landslides... GNS Science researchers used the approaches described in these papers and others to analyse the monitoring data to parameterise the relationships between surface and sub-surface landslide movement patterns and the factors that trigger movement." This monitoring has allowed GNS Science to establish more realistic alerting thresholds than were hitherto possible, and to make quantitative landslide behaviour forecasts for landslide risk management. As stated by Source 2, "in the case of the Taihape landslide, the analysis allowed a recognition that a very large-scale and rapid failure event is unlikely, which secured the future of this part of the town. At Utiku, the monitoring data is currently being used by KiwiRail as the basis for an alert system, to warn when the section of track that crosses the landslide may be prone to deformation".

2. From field-based monitoring to hazard management

DU innovations in field-based monitoring and modelling allow better assessment of unstable slopes that pose risks to human life and infrastructure. We illustrate this direct impact with two examples. In our first example, Focus Humanitarian Assistance (FHA), a NGO in Pakistan, commissioned DU to collaborate on the management of the January 2010 Attabad landslide in the Karakorum Mountains of northern Pakistan, along with the World Bank. This collaboration was based upon prior DU research (Reference 4), as stated by Source 3: "we were aware of the work that Professor Petley had undertaken with his researcher Stuart Dunning on the stability of rockslide dams and on the dynamics of rockslope failure". The landslide created a 180 m high dam which blocked the Hunza River in a particularly narrow section of its valley, creating a lake which filled gradually at first due to low river flows but grew to 21 km long by June. Based on modelling of the deterioration of similar landslide dams (Reference 4), notably the short times (days to weeks) between lake overtopping and catastrophic breaching of the dam, DU staff proposed an upgraded monitoring system, along with early warning systems and evacuation plans that were implemented by 17 downstream communities, an area encompassing the homes of *c.* 25,000 people. Potential scenarios and associated risks posed by the breach of the dam and subsequent downstream flooding were used by DU staff to establish a series of alert states linked to lake levels and flow over the dam. This alert system "was endorsed by the World Bank [Source 4, p. 2 and Annex 3] and was adopted by the government in their response to the crisis" (Source 3). FHA and the National Disaster Management Agency, Government of Pakistan, successfully used the early warning system to predict the time at which the dam began to overtop, and evacuated 15,000 people with no loss of life (Source 3). Monitoring continued until the dam breach risk was reduced when the spillway was re-engineered in 2012. As stated by a senior administrator at FHA (Source 3), "the research of Professor Petley and his colleagues underpinned the response to the Attabad crisis, and Professor Petley's expertise was used directly to both plan the response and to safeguard the local population."

In our second example, rock slope monitoring techniques pioneered by DU research (References 5 and 6) are a primary management tool used by a range of UK commercial and governmental bodies. These include Cleveland Potash Ltd (CPL), owner of the UK's largest non-hydrocarbon extractive mine. CPL produces around 50% of the UK's potash, an organic agricultural fertilizer, and is one of only three UK suppliers of rock salt for de-icing roads. CPL employs more than 1,000 people and is the largest single employer in the North York Moors National Park, contributing £26 million to the local economy annually (see www.bbc.co.uk/news/uk-england-tees-22152699). The background to the impact was summarised in 2006 by the British Geological Survey for the Office of the Deputy Prime Minister (www.mauk.org.uk/sites/default/files/public_files/mpfpotash.pdf), noting that "The proximity of underground workings to the sensitive coastline of the National Park has become an issue. This is because of concern amongst some parties that minor subsidence at the surface associated with extraction might exacerbate rates of coastal erosion... Cleveland Potash has entered into a collaborative research and development project with the University of Durham to gain a better understanding of the natural and anthropogenic influences on the coast."

Within the REF2014 period, CPL has used our longitudinal research on coastal cliff processes to underpin all environmental impact assessments associated with proposed future mine developments. Since 2008 DU research on cliff retreat rates modelled from intensive 3D monitoring has been a fundamental component of impact-mitigation measures associated with successive planning proposals (note that the associated scale and value of these proposals is commercially confidential). The permission to extract granted on the basis of these planning proposals is critical for converting mineral reserves to resources and sustaining the medium-term viability of the mine. As the general manager of CPL notes in relation to a large recent proposal by CPL: "The value of this work to CPL is demonstrated in our recent successful planning application for mineral extraction in the 1.5 km 'coastal corridor'. The research and findings generated by the Durham research formed the basis of the environmental impact assessment that was fundamental in securing this lucrative proposal by providing the best possible dataset on coastal processes and the likely impacts of mining. This dataset was vital in securing this permission, allows us to answer any questions that arise on the impacts of our activities, and demonstrates CPL's commitment as a responsible mining operator. The extraction of this considerable high-grade deposit will form a key part of our ongoing development over the coming decade" (Source 5).

The impact of our work with CPL has cascaded into a series of complementary local projects funded by members of the Northeast Coastal Authorities Group (NECAG), a coalition of all local authorities in northeast England and southeast Scotland, the Environment Agency (EA), and Natural England. Our detailed monitoring work before the REF2014 period redefined the Shoreline Management Plan that covers this 150 km stretch of the UK coast by updating the baseline erosion rates used in prediction calculations, forcing predicted future shoreline positions to be redrawn and enabling continued domestic property insurance for the coastal village of Staithes. This plan (Shoreline Management Plan 2: River Tyne and Flamborough Head 2007, http://www.northeastsmp2.org.uk), which was enacted in 2007 but remains in force to present, stipulated that "the rates of erosion of the cliff [at Staithes] remain uncertain" and mandated continued long-term monitoring and intervention for effective management, recommending continued support for DU surveys (p. 398). As a result of this policy, in 2011 Redcar and Cleveland Borough Council (RCBC) developed an EA-funded active management strategy, using a real-time monitoring network installed and maintained by DU that provides a rockfall alert system for the Cowbar area of Staithes. This proactive approach is based upon 3D monitoring of rockslope failure to provide forewarning of potential impacts on the cliffs and infrastructure above, allowing adaptive management of coastal erosion at this site (Source 6). NECAG affirm that "RCBC commissioned Durham to develop an ongoing, proactive management strategy for Cowbar based upon high-resolution monitoring. This includes the installation of a system in September 2011 and regular visits to site to collect 3D data of the cliff face, which continue to the present. Uniquely, the data generated by this research has enabled us to identify specific locations of increasing erosion, to better determine the long-term rate and the underlying causes of erosion at Cowbar; to my knowledge this is now perhaps the most intensively monitored section of coast in the UK, if not beyond. Regular data capture allows us to keep tabs on activity at Cowbar and to respond as and when appropriate, which would otherwise be impossible to achieve." (Source 6).

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

Source 1: See http://www.gdsinstruments.com/gds-products/gds-shearbase-system;

http://www.gdsinstruments.com/__assets__/products/000031/GDSSS_Datasheet.pdf;

http://www.gdsinstruments.com/gds-products/dynamic-back-pressure-shearbox

Source 2: Testimony letter dated 6/8/13 from Acting CEO and Director of Natural Hazards Division, GNS Science

Source 3: Testimony letter dated 6/8/13 from CEO of Focus Humanitarian Assistance Pakistan

Source 4: Palmieri A (2010) Attabad landslide dam – risk management suggestions. World Bank: http://www.ndma.gov.pk/Documents/Hunza_Landslide_Report/Report%20by%20Mr.%20Allessandro%20%20Palmeiri,%20Lead%20Dam%20Specialist%20of%20World%20Bank%20on%20Hunza%20Landslide.pdf

Source 5: Testimony letter dated 7/8/13 from Managing Director, Cleveland Potash Limited

Source 6: Testimony letter dated 3/6/13 from Coastal Engineer, Redcar and Cleveland Borough Council (and member of Northeast Coastal Authorities Group