Institution: University of Bristol

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Bristol research helps reduce the threat to people and property from snow avalanches

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

Research carried out in the School of Mathematics at the University of Bristol between 1998 and 2005 has been instrumental in the development of structures that arrest or deflect the rapid flow of snow that characterises avalanches in mountainous regions of the world. The research has been embodied in a series of guidance documents for engineers on the design of such structures and many defence dams and barriers have been built across Europe since 2008. The guidance is now adopted as standard practice in many of the countries that experience avalanches. Investment in avalanche defence projects based on the design principles set out in the guidance runs into tens of millions of pounds. The Bristol research is also used internationally in the training of engineers who specialise in avalanche protection schemes. Given the scale of the threat to life and property from these potent natural hazards, the impact of the research is considerable in terms of the societal and economic benefits derived from the reduction of the risk posed by snow avalanches.

2. Underpinning research (indicative maximum 500 words)

Background

Snow avalanches flow at speeds of up to 50 ms^{-1}, transport many tonnes of snow down hillsides, are extremely destructive of infrastructure and lead to many fatalities. With the increasing development of mountainous regions for homes, industry and tourism, there is a pressing need to defend against snow avalanches. One key strategy is to build structures that stop the flow or change its direction. Prior to the publication of comprehensive guidelines on protection dams in 2009 [b], there was relatively little systematic guidance on how to design such structures and very limited understanding of the fundamental dynamics underlying the interaction between flow and obstacle.

The research

Motivated by the devastation and fatalities caused by snow avalanches in Iceland during the 1990s, where several large-volume and rapidly moving flows struck inhabited regions that were thought to be safe from avalanches, Dr Andrew Hogg (University Lecturer, now Reader, in applied mathematics) and his PhD student Kristin Martha Hákonardóttir undertook fundamental research to analyse the interaction between rapid granular flows and rigid stationary obstacles [1]-[4]. This research, led by Hogg, was undertaken in the School of Mathematics, University of Bristol between 1998-2005. Specifically, three types of obstacle were analysed: ‘deflecting dams’ that were supposed to divert the oncoming flow away from the regions to be protected, ‘catching dams’ that were intended to stop the avalanche completely and ‘arresting mounds’ that were meant to dissipate some of the energy of the flow and thus retard the motion. Although such structures had been deployed prior to this research, there was just limited understanding of how effective such measures were and no guidelines on how to optimise their design. This research involved the development of models and laboratory studies at various scales. This combination is vital for research in granular materials where the fundamental governing equations are not fully established.

The work revealed several new phenomena. First, the granular flow could be airborne on impact and jump over the dams and mounds [2]; second, the flow could be transformed abruptly by the deflector (via a ‘granular shock’) into a new flowing state [4]; and third, the flow could be deflected by three-dimensional objects and lose a proportion of its energy [1,3]. In each study, measurements of flow speeds and flow depths at the obstacle provided empirical guidelines for the design of these defence structures.

However, the aspect of the researchers’ contribution that made it most useful for the design of large-scale barriers was the development of predictive models to characterise the flow patterns. For instance, in [4] Hogg and Hákonardóttir demonstrated that ‘hydraulic’-like models could predict accurately the transformation of the flowing state as a function of the upstream, oncoming conditions. In particular, they showed how to calculate the position of the granular shock and the depth and velocity of the flowing material adjacent to the barrier. In [2] they showed how to predict the trajectory of the airborne granular jet, including its launch angle, as a function of the flow and barrier characteristics. Finally, in [1,3] they examined the energy loss in flows deflected by three-dimensional objects, relating it to the layout and size of the obstacles. These models and insights were based upon fundamental scientific principles and permitted the insights gained in the laboratory to be applied at the natural scale.

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

*[1] Hákonardóttir, K.M., Hogg, A.J., Jóhannesson, T. & Tomasson, G.G. 2003 A laboratory study of the retarding effect of braking mounds. *J. Glaciology.* **49**. 191-200 DOI:10.3189/172756503781830692.
*[2] Hákonardóttir, K.M., Hogg, A.J., Batey, J. & Woods, A.W. 2003 Flying avalanches. *Geophys. Res. Letters* **30** DOI: 10.1029/2003GL018172.
[3] Hákonardóttir, K.M., Hogg, A.J., Jóhannesson, T., Kern, M. & Tiefenbacher, F. 2003 Large-scale avalanche braking mounds and catching dam experiments with snow: a study of the airborne jet. *Surveys in Geophysics* **24**, 543-554 DOI: 10.1023/B:GEOP.0000006081.76154.ad.
*[4] Hákonardóttir, K.M. & Hogg, A.J. 2005 Oblique shocks in rapid granular flows. *Phys. Fluids* **17** 077101 DOI: 10.1063/1.1950688.
* references that best indicate the quality of the underpinning research.

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

The impacts of this research are that (i) it underpins and is essentially embodied in modern guidelines on the design of avalanche defence barriers; (ii) it has been used extensively by specialists across Europe who design barriers and has played a crucial part in securing very significant investment in infrastructure through large-scale civil engineering projects aimed at reducing the risk of avalanche damage to settlements; and (iii) the research findings form the basis of highly regarded training courses for avalanche professionals.

Guidelines on design

The research findings on the interaction between obstacles and avalanches and their implications for the design of defence barriers ([1]-[4]) have been disseminated in a series of reports written by professional avalanche researchers that provide practical guidance for avalanche engineers and other users. The following two reports are particularly significant:

Background for the determination of dam height in the SATSIE dam design guidelines (Icelandic Met Office, March 2008) [a]
The design of avalanche protection dams. Recent practical and theoretical developments (European Commission, 2009) [b]

These publications (particularly [b], which is the more comprehensive) are specifically targeted at engineers tasked with designing new structures and they contain many practical guidelines. In [b], research conducted by Hogg and Hákonardóttir forms the basis for Chapter 5 (‘Deflecting and catching dams’) and Chapter 9 (‘Braking mounds’). Additionally, parts of Chapter 6 (‘Special considerations for deflecting dams’) and Appendix D (‘Integrated protective measures – a practical example’) feature several ideas developed by Hogg and Hákonardóttir. This handbook has been reviewed in journals, whose core audience includes civil engineers who design avalanche defences in the public and private sectors internationally. For example, Jomelli concludes that the handbook “represents a useful addition to the technical literature and a good reading opportunity for scientists, engineers and practitioners” [c], while Ancey observes that “Trained engineers and practitioners will find useful information on recent developments concerning avalanche-catching dams” [d].

The scientific guidelines [3,4,b] are also reported in *Handbuch Technischer Lawinenschutz* (2011)[e], a thorough reference book about snow avalanche safety and the design of snow avalanche protection measures, including supporting structures and dams[h]. This is published in German, edited by avalanche professionals from the Austrian Service for Torrent and Avalanche Control [e]; an English version is planned. The book has been well received in the engineering community. Wolfgang Fellin writes that “…the handbook…should become a basic reference for all those involved in avalanche protection and alpine civil engineering” [f]. The guidelines also feature in recently adopted Austrian technical guidelines ONR 24806:2011-12-15: *Permanent technical avalanche protection: Design of structures*, while the new methodology for computing granular shocks [4] has been implemented in software ('WLV-DammTool') and this tool is now used by avalanche professionals across Europe [g].

Investment in infrastructure
The research results [1]-[4], embodied in the new guidelines [b], have been employed at a range of locations in Iceland, thus reducing the risks for villages and other settlements [h]. The economic cost of avalanche damage in Iceland between 1974 and 2000 is estimated at £16M, while there were 69 fatalities. The new avalanche protection measures are intended to avoid such losses [h]. The six projects that have been completed in Iceland since 2008 using the research findings [1]-[4] and new guidelines [b] are at Bíldudalur (€1.9 M), Ólafsvík (€2.3 M), Ólafsfjörður (€1.6 M), Bolungarvík (€9.3 M), Neskaupstaður 1 (€6.2 M) and Neskaupstaður 2 (€10.1 M). (The figures in parentheses are the infrastructure costs of the projects [h].) Currently there are seven projects under construction or in the later stages of design. These are at Patreksfjörður (two projects), Bíldudalur, Ísafjörður (two projects), Siglufjörður and Eskifjörður. Overall, the Icelandic government is spending €5.1M per year on avalanche defence and this level of spending will continue until at least 2020, by which time it is envisaged that most endangered settlements will have been protected [h]. It is assessed that the installation of these various avalanche defence measures significantly reduces the risk of damage to settlements in potential avalanche tracks. For instance, the chief avalanche scientist at the Icelandic Meterological Office writes, "We might guestimate that the risk is in many cases reduced by an order of magnitude...." [h].

The research [1]-[4] and new guidelines [b] also form the basis of the design of a number of defence structures in Norway, with the design work carried out by avalanche engineers at the Norwegian Geophysical Institute [i]. The projects include the dimensioning and design of a deflection dam protecting a power station at Rolandsfjorden in the municipality of Meløy, Nordland county, which was completed in 2011; and the dimensioning and design of protection dams at Rømmingslia, municipality of Oppdal, Oppland county, and for Hotel Alexandria, Loen, municipality of Stryn, Sogn og Fjordane county, and a transformer station in the municipality of Høyanger, Sogn og Fjordane county. In addition, design works are being carried out to safeguard buildings at Kobbelv hydroelectric power station, municipality of Sørfold, Nordland county, and exposed masts of high-voltage power line through avalanche-prone terrain in the municipalities of Naustdal, Høyanger and Sogndal, Sogn og Fjordane county. The cost of such works is approximately £2-3M, but the value of the infrastructure they protect is dramatically higher (at least £100M) [i].

The guidelines for the design of avalanche defence structures [b] have also been adopted by alpine European countries. In France, extensive measures are being constructed at Chamonix to defend against avalanches originating from the Taconnaz glacier. This installation includes mounds and deflecting and catching dams. The investment is approximately €10M and the design, which relies on the research results of Hogg and Hákonardóttir [1]-[4] , was carried out by IRSTEA (French National Research Institute of Science and Technology for Environment and Agriculture)[j]. Researchers from the institute also designed the deflecting dam on the Fougeret avalanche track at Cialancier (Saint-Etienne de la Tinee) in collaboration with RTM ('Restauration des Terrains de Montagne', France)[j], using the research findings [1]-[4] and the new guidelines [b]. The guidelines have also been used in Switzerland by the Institute for Snow and Avalanche Research (SLF) and in Austria, where the Austrian Service for Torrent and Avalanche Control are charged with the responsibility for assessing and managing the risk from avalanches. In the latter case, they have constructed a deflection and a catching dam at Tuiflahn (€1.5M), based on [1]-[4] and [b], which provides protection for 34 dwellings in the most hazardous zones and there are advanced plans for protection measures at Dalfaz to defend 26 buildings with an estimated infrastructure cost of €1.1M [g].

Training
Various training courses for avalanche engineers have drawn heavily on the new approach to modelling the interactions between obstacles and avalanches developed by Hogg and Hákonardóttir [1]-[4]. These include a two-day course in 2012 for professional engineers from

RTM; a half-day course in 2009 for professional engineers from DDT ('Direction départementale des Territoires', Haute-Savoie, France); and contributions to a week-long course in 2010 for engineers from the public and private sectors in France, Italy and Spain under the framework of the European Summer School on Avalanches (Les Deux Alpes, France) [j]. Finally, the research conducted at Bristol has provided in depth training for Hákonardóttir. She subsequently became one of the leading technical engineers on avalanche protection schemes at VST Consulting Engineers, Reykjavik, Iceland.

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

[a] *Background for the determination of dam height in the SATSIE dam design guidelines* (Icelandic Met Office, Int. Rep. 08003, 2008. Authors T. Jóhannesson, Kristín M. Hákonardóttir, C. B. Harbitz and U. Domaas).
Available from http://www.vedur.is/gogn/snjoflod/varnarvirki/08003.pdf

[b] *The design of avalanche protection dams. Recent practical and theoretical developments* (European Commission, Directorate-General for Research, Publication EUR 23339, 2009, ISBN 978-92-79-08885-8, ISSN 1018-5593, DOI:10.2777/12871. Edited by T. Jóhannesson, P. Gauer, P. Issler and K. Lied. Authors: M. Barbolini, U. Domaas, T. Faug, P. Gauer, K. M. Hákonardóttir, C. B. Harbitz, D. Issler, T. Jóhannesson, K. Lied, M. Naaim, F. Naaim-Bouvet and L. Rammer).

[c] V. Jomelli (2009), book review of “The design of avalanche protection dams. Recent and theoretical developments”, *Natural Hazards and Earth Systems Sciences* **9**, 1133-1134.

[d] C. Ancey (2009), review of Jóhannesson, T, Gauer, P., Issler, D. & Lied, K. (eds) “The design of avalanche protection dams. Recent and theoretical developments”, *J. Glaciology* **55**,753-754. DOI: 10.3189/002214309789470888

[e] *Handbuch Technischer Lawinenschutz*. Edited by Florian Rudolf-Miklau and Siegfried Sauermoser. Berlin, Wilhelm Ernst & Sohn, Verlag für Architektur und technische Wissenschaften GmbH & Co. 466 pp. ISBN: 978-3-433-02947-3 (see: http://www.ernst-und-sohn.de/handbuch-technischer-lawinenschutz and http://www.amazon.co.uk/Handbuch-Technischer-Lawinenschutz-Florian-Rudolf-Miklau/dp/3433029474).

[f] W. Fellin (2011) Book review of “Handbuch Technischer Lawinenschutz”, *Geomechanics and Tunnelling* **4**, 704. DOI: 10.1002/geot.201190055

[g] Personal communication from Head of Snow and Avalanche at Austrian Service for Torrent and Avalanche Control.
This scientist corroborates the use of the research [1]-[4] and design guidelines [b] in Austria, the construction and plans for construction of avalanche protection measures at Tuiflahn and Dalfaz and the development of the software WLV-DammTool.

[h] Personal communication from Chief Avalanche Scientist at Icelandic Meteorological Office.
This scientist corroborates the many avalanche protection measures deployed in Iceland, along with their infrastructure costs and risk reduction. He confirms the continued spending and the centrality of the research [1]-[4] in the guidelines for the design of dams, deflectors and barriers[b,e].

[i] Personal communication from Senior Physicist, Natural Hazards, Avalanches and Rockslides at Norwegian Geotechnical Institute.
This scientist confirms the application of the research [1]-[4], embodied in the new guidelines [b], to avalanche defence measures in Norway.

[j] Personal communication from Researcher at Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (IRSTEA).
This researcher confirms the design of the constructed avalanche defence measures in France employed the research [1]-[4] embodied in the new guidelines [b], and their infrastructure costs. He also corroborates that aspects of the training courses for avalanche professionals were based on these materials.