

<b>Institution: University of Aberdeen</b>
<b>Unit of Assessment: 15 (General Engineering)</b>
<b>Title of case study: Ground-Anchorage Integrity Testing (GRANIT)</b>
<p><b>1. Summary of the impact</b></p> <p>The GRANIT system is a non-destructive technique for assessing the condition of rock bolts and ground anchors used to support structures such as tunnels. It applies a small impulse to the bolt and interprets the resulting vibration response to provide estimates of load and unbonded length. Initial development of the system was based on the findings of EPSRC projects in tunnels undertaken by the Universities of Aberdeen and Bradford from 1989-1997, resulting in an empirically based method. However, research undertaken at the University of Aberdeen since 1998 has provided the understanding of the process and developed the fundamental engineering science needed to underpin the development of a full commercial system. The GRANIT system is patented, and has been subject to worldwide licence to Halcrow who have undertaken testing and provided a method of ensuring the safety of mines, tunnels and similar structures. Halcrow received the NCE award for Technical Innovation Award for GRANIT in December 2010. The impact of the research has been in part economic, but largely on practitioners and professional services.</p>
<p><b>2. Underpinning research</b></p> <p>The initial patent for GRANIT (WO95/27831) was granted in 1995 and was based on findings from joint EPSRC projects undertaken by the Universities of Aberdeen and Bradford from 1989-1997. These projects showed that the vibration of rock bolts changed with the load they carried. This is the property/effect on which the initial GRANIT development was based despite its empirical nature. The majority of the research which produced a clear understanding of the dynamics of rock bolts and ground anchors, and so provided the science which underpins the interpretation of results from the GRANIT system, was carried out by a team comprising Prof A Rodger and Drs A Ivanovic, R Neilson and A Starkey during the period 1998-2010. Ivanović and Starkey were initially PhD students and research assistants under the supervision of Rodger and Neilson during the period 1998-2001, then became research fellows and ultimately full academic staff in 2003 and 2005 respectively. During the period 1998-2004 aspects of this work were undertaken with Amec, the licensee at that time, who provided access to field data.</p> <p>The research undertaken by Ivanović [1] produced a dynamic model of ground anchorage systems, which explained the shift in frequency observed by Rodger in his work with Bradford. In particular it explained the importance of the nonlinear stiffness of the anchor head and the effect of free length in the dynamics of the rock bolt. Both aspects/characteristics are critical to the use of GRANIT in a commercial environment and were not understood until this point. Starkey's research [2] identified the parameters in the GRANIT system, which most affect the quality of the data obtained and applied artificial intelligence methods to provide a means of interpreting the data. The research was pulled together to provide a system which could be trained using the model. [3] Improvements to the GRANIT device itself were undertaken by Neilson during that period [4], developing a dynamic model to optimise the system and improve signal quality.</p> <p>Recent research by Ivanović and Neilson (2005-12) has resulted in better understanding of the various modes of vibration within the rockbolt system [5], an aspect of interest in trying to use the GRANIT system to determine total anchorage length. Being able to estimate total length of a bolt is</p>

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of great importance to the mining industry in preventing tunnel collapse due to broken bolts. Other recent work includes the examination of the effects of changes to the anchor head design and how these affect the dynamics and the effects of de-bonding due to loading [6] and the effect this has on the rock bolt response. The latter explains shifts in frequency seen during field-testing and rock bolt installation by Amec.

An EPSRC funded project led by Ivanović has investigated the use of the system for multi-strand anchorages and has developed a head assembly, which optimises the use of GRANIT on such anchors, expanding the systems applicability. The design is based on a patent granted to the University in 2006 (WO 2006018656 (A1), Improved Anchorage Head Assembly) which is based on the earlier research. The project was supported by DYWDAG a major supplier of anchorage systems. Research into the use of GRANIT on soil anchorages has also been supported by the EPSRC and NRP.

### 3. References to the research

1. Ivanović, A., Neilson, R. D. and Rodger, A. A., 2001, "*Lumped Parameter Modelling of Ground Anchorage Systems*" Geotechnical Engineering 149 (2), 103-113.
2. Starkey A., Ivanović A., Rodger A. A., Neilson R.D., 2003, "*Condition Monitoring of Ground Anchorages by Dynamic Impulses: GRANIT System*" Meccanica, 38, p265-282.
3. Starkey, A., Ivanović, A., Neilson, R.D. and Rodger, A. A., 2003, "*Using a lumped parameter model of a rock bolt to produce training data for a neural network for diagnosis of real data*", Meccanica, 38, p131-142.
4. Neilson, R. D., Ivanović A., Starkey A. J. and Rodger, A. A., 2007, "*Design and Dynamic Analysis of a Pneumatic Impulse Generating Device for the Non-destructive Testing of Ground Anchorages*", Mechanical Systems and Signal Processing, 21, 6, 2523-2545.
5. Ivanović, A and Neilson, R. D., 2008, "*Influence of geometry and material properties on the axial vibration of a rock bolt*", International Journal of Rock Mechanics and Mining Sciences, 45, 6, 941-951.
6. Ivanović, A. and Neilson R D. "*Modelling of Debonding Along the Fixed Anchor Length. 2009*", International Journal of Rock Mechanics and Mining Sciences, 46, 4, 699-707.

### 4. Details of the impact

The impact of the GRANIT research has been twofold: firstly, economic impact through the generation of commercial returns to Halcrow via the technology licence; secondly, in the adoption of such methods in the wider industry in terms of Impact on practitioners and professional services. The Impact described here is interim in nature, in that the licence arrangements with Halcrow have now been terminated. The technology is now in the process of being relicensed with discussion being held with Rio Tinto Zinc (RTZ) and other groups with a view to penetrating the mining sector.

GRANIT is the first fully commercial system for testing rock bolts and ground anchorage systems. Rock bolts and ground anchors are used to support tunnels, mines, dams and other large structures and in the past it has been difficult to test these to ensure they are functioning correctly and holding the correct load. The GRANIT system can be used to estimate the load in the bolt/anchor, the un-bonded length, and to identify bolts which respond in a markedly different manner to those around them (exception testing). The measurement of these parameters is important in assessing the condition of bolts/anchors and ensuring the safety of the structure they

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support. In mines, literally millions of rock bolts are used to support roadways. The effective grouting of these into the surrounding strata is important in ensuring the integrity of the roof structure, and so to prevent potentially fatal rock falls.

Early testing of rock bolts supporting the roof in UK Coal's Thoresby mine, during development with Amec, identified a number of bolts which were "different" from the others and which the research team identified as either being bonded inadequately into the strata or damaged. Subsequently these bolts were exhumed and all were found to either have been poorly bonded or broken, validating the method [1]. Identification of these bolts allows remedial measures to be taken before the occurrence of failure of the roof structure.

Deployment in Rio Tinto's North Parkes mine in Australia to test the cable bolts holding up a cavern for processing equipment, resulted in the identification of incorrect bolt installation in the cavern roof. The specification had called for 6m bolts in the walls with 10m bolts supporting the roof. Instead, 6m bolts had been used throughout leaving the roof with insufficient support. This would have been impossible to identify visually and would not have been detected without use of the GRANIT system. [2]

During 2012 and early 2013, detailed discussions were undertaken with RT regarding application of the technology within mining operations in Indonesia and Mongolia. This has involved the discussion of an integrity inspection programme to ensure the installation quality of the 10 million bolts to be installed within RT mining operation over the next 10 years. The capital cost of installing these bolts will exceed \$1B as an integral part of the operation. The support they provide is an integral part of the operation represent ensuring personnel can work safely in the various mine openings and the tunnel functionality and reliability. The failure of support systems and the subsequent impact on operations can be very be severe. At one operation it is estimated that over \$500M of ore has been left behind because of premature bolt failure. A number of assessments have been made that up to 20% of the installed support (bolts) are ineffective either due to poor quality installation or wrong location. The potential cost savings and safety improvements that a system such as GRANIT would provides due to improved maintenance and replacement regimes are substantial and are estimated to be in excess of \$300M for RT operations alone. [1] The interest in the research outcomes from GRANIT and the perceived benefits to RT are in ensuring the quality of the installed support system and indicating where modifications additional support is needed.

During the REF period (2008-2012) the system was licensed to Halcrow who provided the service from their Australia, United Arab Emirates and USA offices. Halcrow received the New Civil Engineer Tunnelling Awards Technical Innovation Award for GRANIT in 2010 [3]. The license included the use of copyrighted software (an Integrated Analysis System) produced by the University of Aberdeen, based on the model developed by Ivanović and the neural network approach developed by Starkey. This automates the process and allows Halcrow operatives to build a model of the anchor system and use this for analysis in cases where it is not possible to undertake testing on reference bolts/anchors.

The significance of GRANIT is in its ability both to improve workers' safety and potentially to reduce costs associated with remedial work or failure of a structure. The reach of the system has been global with deployment in Canada, Greece, UK and Australia.

**5. Sources to corroborate the impact**

1. A General Manager at the Underground Technology Centre, Technology and Innovation, Rio Tinto, can corroborate the impact of the use of the GRANIT system.

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2. New Civil Engineer Award for technical innovation 2010; <http://www.nce.co.uk/Story.aspx?storyCode=8609403> and <http://www.abdn.ac.uk/news/3898/>.
3. First prize for technical innovation, Ground Engineering Awards, 2012. (A copy of the Ground Engineering Awards 2012 winners supplement available on request from HEI).