Institution: University of Sheffield

Unit of Assessment: 14 - Civil and Construction Engineering

Title of case study: Rapid analysis and design software for engineers

1. Summary of the impact

Novel numerical limit analysis methods developed in the Department of Civil and Structural Engineering have been embedded in commercial software developed by spin-out company LimitState (http://www.limitstate.com). The software is now used by over 100 industrial organisations in more than 30 countries.

The software can model real-world problems far more quickly (up to 50 times faster) than was previously possible, bringing significant productivity and economic benefits to practitioners and their clients, e.g.:

- Up to £500k saved on a weekly basis by a single organisation due to new 'rapid response' offshore design capability;
- £500k saved by a client on a single project, due to the software showing that a planned bridge strengthening programme was unnecessary.

2. Underpinning research

Underpinning research in the field of numerical limit analysis and design was undertaken in the 1990s and 2000s by Matthew Gilbert (Professor, joined Sheffield 1993), Colin Smith (Senior Lecturer, joined Sheffield in 1992) and Andy Tyas (Reader, joined Sheffield in 1993):

- Gilbert carried out research on using rigorous mathematical optimisation techniques to identify the locations of sliding/hinging discontinuities in masonry block structures (e.g. masonry bridges), enabling the margin of safety to be established reliably, without the need to resort to ad-hoc methods [R1]. Research designed to improve the efficiency and practicality of the methods developed was later supported by Network Rail and via an EPSRC doctoral studentship (doctoral student Husham Ahmed – now at Mott Macdonald and still utilising LimitState software there in 2012) [G1], and later by the International Union of Railways.
- Subsequently Gilbert and Tyas, supported via an EPSRC doctoral studentship (Pritchard – now working at spin-out company LimitState), undertook further research on applying mathematical optimisation techniques to engineering problems, focussing particularly on identifying the most efficient arrangement of bars in trusses ('Layout Optimisation'). A key outcome of this work was the development of a new technique which permitted problems to be tackled which were larger, by several orders of magnitude, than those described in existing literature [R2].
- Gilbert and Smith then secured EPSRC grant funding in 2004 [G2] to explore the potential for mathematical optimisation techniques to be applied to a wide range of challenging analysis and design problems.
- One challenging analysis problem, which had remained unsolved for decades, involves automatically identifying the geometry of potential collapse mechanisms in geotechnical and other constructions. Smith and Gilbert were able to show that 'Layout Optimisation' techniques could be used to solve this problem, though in this case identifying the layout of discontinuities defining the failure mechanism ('Discontinuity Layout Optimisation', DLO) [R3].

The benefit of the rigorous numerical limit analysis methods developed (e.g. those suitable for masonry bridge and geotechnical applications) is that a very wide variety of potential failure mechanisms can be rapidly evaluated, far larger than can be considered by hand or when using ad-hoc search methods.

In the case of DLO, on a desktop PC upwards of *two to the power of a billion* possible layouts of discontinuities defining a failure mechanism can be considered. As the blocks of material between

discontinuities can subsequently be identified, DLO effectively for the first time fully automates the process of identifying the geometry of potential collapse mechanisms [R3], and can be extended to treat a wide variety of practical problems. Furthermore, unlike finite element based alternatives, DLO can inherently handle singularities in stress and/or displacement fields. Since these are common features of most collapse mechanisms, this means that solutions to real-world problems can be obtained much more rapidly than before, giving engineers a powerful new analysis and design tool.

[G1] Network Rail Sponsorship of EPSRC Studentship: 'Computational limit analysis of concrete and masonry bridges', Investigator: Gilbert, M., 2001-04. Value £12,000.

[G2] EPSRC Grant, GR/S53329: 'Application of novel computational limit analysis and design synthesis methods in structural engineering (Advanced Fellowship)', Investigator: Gilbert, M., 2004-09. Value £225,560. Also associated EPSRC Grant GR/S53336: 'Holistic limit analysis and retrofit design synthesis for masonry arch bridges', Investigators: Gilbert, M. and Smith, C., 2004-07. Value £63,531.

3. References to the research **Denotes most significant outputs for this impact case study.*

R1. *Gilbert, M. and Melbourne, C., 'Rigid-block analysis of masonry structures', *The Structural Engineer*, Vol. 72, No. 21, pp. 356-361, 1994. *Describes how optimisation can be used to analyse complex multi-span, multi-ring, masonry arch structures.*

R2. *Gilbert, M. and Tyas, A., 'Layout optimisation of large-scale pin-jointed frames', *Engineering Computations*, Vol. 20, No. 8, pp. 1044-1064, 2003. doi: 10.1108/02644400310503017. *Describes the development of an efficient procedure which allows very large-scale layout optimisation problems to be solved on a PC. This later meant that the DLO procedure could be used to solve many real-world scale problems in seconds.*

R3. *Smith, C.C. and Gilbert, M., 'Application of discontinuity layout optimisation to plane plasticity problems', *Proceedings of the Royal Society A*, Vol. 463, pp. 2461-2484, 2007. doi: 10.1098/rspa.2006.1788. *First paper to describe the DLO procedure, and its application to various benchmark problems.*

R4. Smith C.C., Gilbert M., 'Data processing method and method'. Patent number: US 8,140,175. Application number: 12/443,713. Filed date: 01 Oct 2007. Awarded date: 20 Mar 2012; EU Patent pending. *Patent describing the DLO procedure, currently licensed by the University of Sheffield to LimitState Ltd.*

4. Details of the impact

The main impacts arising from this research are:

- **impact on practitioners**, through the availability of efficient new methods of analysis and design;
- **economic impact**, principally through cost savings realised by practitioners using the software, and/or realised by their clients.

Process

To help realise the potential of the numerical limit analysis method developed for masonry block structures, in 1999 funding from Railtrack (now Network Rail) was secured to develop the RING analysis software application for masonry arch bridges. This was then made publicly available in 2001 (over 10,000 download keys were issued to users in over 40 countries worldwide over the period 2001-07, with usage of the software continuing beyond this period).

This success led to the decision in 2006 to form a new spinout company, LimitState Ltd, to exploit numerical limit analysis research being undertaken at Sheffield, and to develop a range of software applications:

- Following a £50k investment in the company by Bestech Systems, a completely re-engineered version of the RING software, **LimitState:RING**, was launched in 2007 at the International Union of Railways HQ in Paris. (Doctoral student Darwich, sponsored by Buro Happold and later employed by LimitState, played an important role in ensuring large parts of the software were generic, facilitating re-use in other limit analysis and design software products).
- Funding of approx. £100k was secured from South Yorkshire Investment Fund, Bestech Systems and Sheffield University Enterprises Limited to support development of DLO-based software, and patent protection was secured to protect the IP covering the DLO method [R4]. The DLO-based **LimitState:GEO** geotechnical analysis and design software was launched at the Institution of Civil Engineers HQ in London in 2008 and was shortlisted for a NCE/Civils Innovation Award the same year. (Gilbert took a 6 month abeyance from his EPSRC Advanced Fellowship [G2] to help finalise the software and to publicise this in the geotechnical engineering community.)

LimitState continue to actively develop and market both software applications, via advertising in technical publications, at trade events and by running seminar/training events for industry in the UK and abroad, often inviting Gilbert and/or Smith as speakers (over 20 full and half day events run to date).

Impact on Practitioners

The limit analysis software developed by LimitState effectively bridges the gap between hand-type analysis methods (often automated in simple software applications or spreadsheets) and significantly more complex tools (e.g. non-linear finite element analysis), which respectively tend to over-simplify a problem or require significant user expertise and computational resources. This makes LimitState software unique in the market and extremely attractive to practitioners.

Currently over 100 industrial organisations licence LimitState software, located in more than 30 countries worldwide [S1]. Each product has a similar number of users, with some organisations licencing both products. Organisations currently licencing the software include:

- **Consultants:** Arup, Atkins, Jacobs, URS, WSP, Aecom, Amey, Arcadis, Bilfinger, Grontmij, Halcrow, Halcrow, Hyder, May Gurney, SKM, WYG.
- **Infrastructure owners:** Network Rail, SNCF, Railcorp (Australia), OBB (Austria), also numerous local authorities in the UK and Eire.
- **Contractors:** Balfour Beatty, Carillion, Costain, Interserve, Laing O'Rourke, Vinci.
- **Offshore:** Advanced Geomechanics, Fugro, GL Noble Denton, [text removed for publication].

Users of both LimitState:RING and LimitState:GEO have reported significant productivity gains (up to approx. 50 times faster modelling capability) and the ability to gain deeper insights into potential modes of behaviour (the visual output is very easy to interpret, and is also useful when communicating analysis and design issues to non-expert stakeholders).

Specifically, LimitState:RING allows practitioners to rapidly identify potential failure mechanisms in complex masonry arch bridge structures which cannot be found easily using alternative tools [S2], whilst LimitState:GEO means that practitioners can move beyond simplistic hand-type calculations for constructions such as slopes, retaining walls and footings, but without having to turn to significantly more complex tools (e.g. non-linear finite element analysis), which are generally much more time-consuming and expensive to use [S3]. For example:

- On a major stadium project, civil engineering contractor Laing O'Rourke encountered site conditions which necessitated redesign of the foundations of the principal elements; with LimitState:GEO this was completed in a couple of hours – alternatives would have taken days or weeks, leading to costly programme delays. They have also reported that '*we find the software invaluable for quickly and reliably answering the kind of questions we often face as*

contractors, such as 'How close can we safely place this 120t piling rig to the crest of our temporary slope?'. And because the software doesn't prejudge the type of failure mechanism that will be critical we sometimes get surprises – for example finding that a local bearing capacity failure might be more critical than the global slope failure we had anticipated - something that our traditional slope stability analysis package would not necessarily have identified' [S4].

Economic Impact

Significant economic impacts have been realised by practitioners using the software (and/or by the clients of these practitioners). Indicative examples from two of the 100+ users are provided below:

- [text removed for publication] company that has been applying LimitState:GEO to a variety of offshore engineering problems, observing that *'in addition to the insights we get from using the software we also see a massive improvement in productivity*'. In the offshore sector this quickly translates into multi-million pound annual savings: *'If we had used hand calculations and FEA we could not have reached a workable design that we could install from our vessels in the time available. We would have needed to use a heavy pile driven to depth, and this would have cost us in the order of £500k in direct project costs. Similar examples, where direct costs are avoided due to reduced conservatism, reduced operational inefficiencies or potential failures can be observed on a weekly basis across our project portfolio, leading to current and projected future annual savings of between £5 million and £10 million'.*
- Kier MG (formerly May Gurney), a consultant working on behalf of Network Rail, reported that they saved their client £500k on a single bridge when using LimitState:RING (by demonstrating that the programmed strengthening work was in fact unnecessary) [S6].

The significant productivity and economic benefits outlined above is in turn helping LimitState to grow worldwide product revenues (>350% increase in the last 5 years) [S1], and this is expected to continue.

5. Sources to corroborate the impact

S1. Chairman of LimitState Ltd. For confirmation of customer names and the numbers of users by country (see also: http://www.limitstate.com/clients). Also to confirm the company's product revenue growth.

S2. CIRIA C656: Masonry arch bridges: condition appraisal and remedial treatment (2006), p254. Indicates that the rigid block method of analysis represents 'a significant improvement from basic limit analysis formulations' and can model 'much more complex mechanisms'. (LimitState:RING is the only commercial software to use this method of analysis.)

S3. Ballard, J.C. et al (2010) Simplified VH equations for foundation punch-through sand into clay, Frontiers in Offshore Geotechnics II, Ed. White, D., pp. 655–660, CRC Press, 2010. DOI: 10.1201/b10132-91. Corroborates the comparative speed of LimitState:GEO, stating that '*Solutions within 10% tolerance could generally be obtained within a few minutes compared to several hours with Plaxis*'. (Plaxis is a very popular finite element analysis program for geotechnical applications.)

S4. Senior geotechnical engineer from Laing O'Rourke (UK). For confirmation of the accuracy of the text given in section 4.

S5. [text removed for publication].

S6. Director of Professional Services at Kier MG. For confirmation that Network Rail saved £0.5M when Kier MG (formerly May Gurney) used LimitState:RING to assess one of their bridges.