

Institution: The University of Edinburgh
Unit of Assessment: B7 – Earth Systems and Environmental Sciences
Title of case study: DEVELOPMENT OF OPERATIONAL EARTHQUAKE FORECASTING SERVICES
<p>1. Summary of the impact</p> <p>Impact: Multi-national developments in public policy and service provision related to earthquake risk reduction, derived from the work of the International Commission on Earthquake Forecasting for Civil Protection (ICEF), established following the 2009 L'Aquila earthquake.</p> <p>Significance and reach: In 2012 the Italian Department of Civil Protection allocated €1billion for seismic protection, including a multi-year programme on operational earthquake forecasting. New programmes/policies have been enacted by government bodies in the USA (2012), Russia (2012) and Japan (May 2013).</p> <p>Underpinned by: Research into earthquake dynamics and predictability, undertaken at the University of Edinburgh (1996 onwards), which led to the appointment of the sole UK representative to the ICEF.</p>
<p>2. Underpinning research Numbered references refer to research outputs in Section 3.</p> <p>Key researchers The start and end dates of continuous employment in the School of GeoSciences, University of Edinburgh, are shown along with the most recent / current position of each researcher.</p> <p>Main, Professor of Seismology and Rock Physics (1989 onwards) Huc, NERC-funded Post-Doctoral Researcher (2000 - 2003) Li, ITF JIP and DTI-funded Post-Doctoral Researcher (2003 - 2006) Naylor, RSE Research Fellow (2004 onwards)</p> <p>Research overview and context Research by the Edinburgh group led by Main over the period 1996-present has explored multiple aspects of earthquake predictability, approaching the question both from statistical and rock physics perspectives. This body of research has provided a clear theoretical framework for the practical difficulty of accurately predicting individual earthquakes - 'the holy grail of earthquake science' [1,2,3] – while also allowing a finite degree of low-probability forecasts of populations of events, including triggering processes [4]. It has established appropriate theories and methodologies for the evaluation of long-term earthquake hazard [5] and for constrained earthquake nucleation processes [2,3]. Based on this wide-ranging expertise, Main was also a co-author on the 2011 International Commission on Earthquake Forecasting for Civil Protection (ICEF) scientific report [6].</p> <p>Key research findings that underpin the subsequent impact Research published by Main in 1996 demonstrated that the theory of self-organised criticality for earthquake population dynamics had significant implications for practical aspects of earthquake hazard estimation and earthquake predictability [1]. In summarising a subsequent 1999 <i>Nature</i> website debate on earthquake prediction, Main concluded that while prospects for the reliable prediction of individual earthquakes seemed remote, probabilistic forecasting above the background hazard rate was feasible and was consistent with the theory.</p> <p>Subsequent work, published between 2003 and 2006, has gone on to investigate statistical aspects of earthquake predictability in more detail. Quantification of the probability of earthquake clustering by triggering as a function of time and distance using global digital earthquake data</p>

Impact case study (REF3b)

demonstrated and quantified a significant probability gain over the random background at distances up to 150 km [4]. In a second study, formal statistical model selection techniques in the presence of uncertainty have revealed on-going difficulties in the practicalities of detecting reliable, statistically significant, earthquake precursors, specifically changes in seismic anisotropy [2]. A third study demonstrated significant epistemic uncertainty to probabilistic forecasting of extreme events through the use of a frequency-magnitude distribution, by demonstrating that a single earthquake – the 2004 Boxing Day event in Sumatra – completely changed the best-fitting distribution to a pure power law in seismic moment [5].

Within a complementary rock physics approach, the development of a model for the quasi-static nucleation of unstable fracturing and slip has shown that such a model can be consistent with those from material science and percolation theory [3]. The resulting highly non-linear behaviour provides a rationale for the practical difficulty of accurately forecasting the failure time in brittle failure events, even in controlled laboratory and engineering settings.

3. References to the research

Comments in bold on individual outputs give information on the quality of the underpinning research and may include the number of citations (Scopus, up to September 2013) and/or the 2012 Thomson Reuters Journal Impact Factor (JIF). The starred outputs best indicate this quality.

[1]* Peer-reviewed review article with Main as sole author, >220 citations, JIF: 13.9

Main, I.G. (1996) 'Statistical physics, seismogenesis, and seismic hazard', *Rev. Geophys.* 34, 433–62, DOI: 10.1029/96RG02808

[2] Peer-reviewed journal article (Seher was a UG student at Edinburgh 1999-2003)

Seher, T., and Main, I. G. (2004) 'A statistical evaluation of a 'stress-forecast' earthquake', *Geophys. J. Int.*, 157, 187–193, DOI: 10.1111/j.1365-246X.2004.02186.x

[3] Peer-reviewed journal article

Main, I.G. (1999) 'Applicability of time-to-failure analysis to accelerated strain before earthquakes and volcanic eruptions', *Geophys. J. Int.* 139, F1–F6, DOI: 10.1046/j.1365-246x.1999.00004.x

[4]* Peer-reviewed journal article, >30 citations, JIF: 3.2

Huc, M. and Main, I. G. (2003) 'Anomalous stress diffusion in earthquake triggering: correlation length, time dependence, and directionality', *J. Geophys. Res.* 108 (B7), 2324, DOI: 10.1029/2001JB001645

[5] Peer-reviewed journal article

Main, I. G., Li, L., McCloskey, J., and Naylor, M. (2008) 'Effect of the Sumatran mega-earthquake on the global magnitude cut-off and event rate', *Nature Geoscience* 1, 142, DOI: 10.1038/ngeo141

[6]* Peer-reviewed journal article representing the scientific findings of ICEF, >20 citations in two years

Jordan, T., Chen, Y., Gasparini, P., Madariaga, R., Main, I., Marzocchi, W., Papadopoulos, G., Sobolev, G., Yamaoka K. and Zschau, J. (2011) 'Operational earthquake forecasting', *Annals of Geophysics* 54(4), 361–91, DOI: 10.4401/ag-5350

A further metric of research quality is given by the peer-reviewed grants that have contributed to the preceding outputs, which include:

- *Earthquake and Failure Forecasting in Real Time (EFFORT)* (2011-2013), sponsor: NERC (NE/H02297X/1), value £527k, awarded to Main with A. Bell, P. Meredith (UCL)
- *Novel Approaches to Networks of Interacting Autonomes (NANIA)* (2004-2008), sponsor: EPSRC, value £440k, awarded to: G. Ackland (Edinburgh, Physics) with Main and others.
- *Triggering of Instabilities in Materials and Geosystems (TRIGS)*, (2007-2009), sponsor: EU Framework 6, value €239k, awarded to S. Zapperi (Milan), with Main and others.

4. Details of the impact

Lettered references relate to corroboration sources in Section 5.

Public policy and service provision related to earthquake risk reduction (Primary Impact)

Pathway: The research undertaken by the Edinburgh group led to the appointment of Main, as the sole UK representative to the International Commission on Earthquake Forecasting for Civil Protection (ICEF), which was established following the 2009 L'Aquila earthquake. The Findings and Recommendations of ICEF were presented to the public in September 2009 [A] and re-affirmed current practice in earthquake forecasting for civil protection, including long-term planning for building regulation and the lack of accurate prediction methods sufficient to justify general evacuation. Recommendations centred on the implications of statistically significant but low absolute probability (<1%) forecasts due to earthquake clustering, along with the communication of uncertainty in risk estimation, topics for which the underpinning research in Section 2 is directly relevant. The direct influence of Main's research work on their appointment to the panel and its subsequent findings can be verified by the chair of ICEF [B], as well as Main's co-authorship of the subsequent peer-reviewed scientific report ([5], Section 3). The international profile of the ICEF report has then led to multi-national developments in public policy and the provision of operational services for earthquake forecasting (2011 – May 2013). The ICEF report was also cited in the UK government Foresight programme report (2012) on 'Anticipation of Geophysical Hazards' [C].

Significance and reach:

- The Italian Department of Civil Protection (DPC) took the ICEF recommendations seriously and acted quickly. In a letter to the ICEF in June 2012, the head of the Italian DPC wrote "*many DPC activities are descending from your findings and recommendations*" which include: "*a ten-year research programme on operational earthquake forecasting*" and "*one billion Euros in seven years were allocated by the Italian Government for seismic prevention*" [D]. The practical implementation of these commitments can be verified by independent experts in Italy [E]. The letter also confirmed that DPC had implemented "*your suggestion to convene a special advisory structure reporting to the head of DPC...while reorganising the Commissione Grande Rischi, appointed by the Prime Minister*" [D], which will act to separate scientific advice from operational decision making and risk communication.
- The following countries have also made changes to policy and/or service provision based on direct citation of the ICEF report. In 2011 a U.S. National Research Council report on National Earthquake Resilience called for a program of operational earthquake forecasting [F] and in 2012 the U.S. Geologic Survey began such a program [B]. In 2012, it was confirmed that: I) the "*Russian Geophysical Survey has begun a new project on earthquake forecasting in Kamchatka*" [G] and II) the Greek national authority for the co-ordination of anti-seismic policy would undertake actions for the implementation of the ICEF's recommendation. In May 2013, a Japanese government task force re-examined hazard mitigation policy for large earthquakes along the Nankai trough [H].

Public engagement with, and understanding of, earthquake risk science (Secondary Impact)

Pathway: Following the L'Aquila disaster, legal proceedings were begun against the officials involved in communicating the earthquake risks and the subsequent trial (in which the ICEF report was cited in evidence by the defence team) generated much media discourse. Main contributed to the public understanding of these complex issues by discussing them in a range of international media and a sustained series of engagements with various BBC radio and online programmes.

Significance and reach: Following on from a BBC Radio 4 'Material World' programme in 2010, Main has participated in two other BBC Radio 4 programmes, 'More or Less' and 'Today' (Radio 4 has a UK reach of up to 10.98M in quarterly 2013 Radio Joint Audience Research figures) and a BBC News Website (circulation ~30M) piece on the topics of L'Aquila and scientific assessment and communication of risk [I].

5. Sources to corroborate the impact

Where two web-links are given, the first is the primary source and the second an archived version.

[A] Executive summary of 'Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization', ICEF (October 2009)

<http://tinyurl.com/B7-6-S5-XA> or <http://tinyurl.com/B7-6-S5-A>

Provides corroboration of Main's co-authorship of the ICEF Findings and Recommendations report (Page 9).

[B] The Chair of the International Commission on Earthquake Forecasting for Civil Protection

Can provide corroboration that: I) Main's research work informed the commission's findings and recommendations, II) Main contributed significantly as an individual to the report as one of its primary authors, and III) the report had the impact cited above on US Public Policy and Services.

[C] UK Foresight programme (Department for Business, Innovation and Skills) report on 'Anticipation of Geophysical Hazards' (November 2012)

<http://tinyurl.com/B7-6-S5-XC> or <http://tinyurl.com/B7-6-S5-C> The ICEF scientific report is cited on page 15 of this document.

[D] Letter from the head of the Italian Department of Civil Protection to the ICEF president and commission (July 2012)

<http://tinyurl.com/B7-6-S5-D> or available upon request. Provides corroboration of the various quoted statements given in Section 4.

[E] Dirigente di Ricerca (Senior Researcher) at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy

Can provide corroboration that the DPC has initiated a 10-year joint programme with INGV on earthquake monitoring and operational earthquake forecasting.

[F] US National Research Council report (2011)

'National Earthquake Resilience: Research, Implementation, and Outreach', Hamilton, R.M., et al., 2011, National Academies Press, Washington, D.C., 198 pp, ISBN-13: 978-0-309-18677-3
Provides corroboration that the ICEF scientific report is cited (Page 196).

[G] Professor, Institute of Physics of the Earth in Moscow, Russia

Can provide corroboration of the quoted statement given in Section 4 and that it stems from the recommendations of the ICEF report.

[H] Chair of the Task Force on the Predictability of Great Earthquakes along the Nankai Trough, Nagoya University

Can provide corroboration of the importance of the ICEF report in the commission of the task force.

[I] Selected media coverage involving Main on the topic of earthquake risk (2010 - 2012)

I) BBC Radio 4 'Material World' programme on L'Aquila (15 July 2010) <http://tinyurl.com/B7-6-S5-XI1>

II) BBC Radio 4 / World Service 'More or Less' programme on Communicating Risk (6 April 2013)

<http://tinyurl.com/B7-6-S5-XI4> or <http://tinyurl.com/B7-6-S5-I4> (Main is named as a contributing expert in the 'More Programme Information' section)

III) BBC Radio 4 'Today' programme (27 December 2012)

IV) BBC News website story 'L'Aquila Ruling: Should Scientists Stop Giving Advice?', 27 October 2012 <http://tinyurl.com/B7-6-S5-XI3> or <http://tinyurl.com/B7-6-S5-I3> (Main named in first paragraph)

Collectively these media pieces provide corroboration of a sustained programme of public engagement around the theme of earthquake predictability.