Institution: University of Edinburgh

Unit of Assessment: 7

Title of case study: Development and implementation of Operational Earthquake Forecasting (OEF) for managing and communicating seismic risk

Period when the underpinning research was undertaken: January 2000 – 31 December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Ian Main	Professor of Seismology & Rock Physics	04/1989 – present
John McCloskey	Professor of Natural Hazards	07/2016- present
Mark Naylor	Senior Lecturer in Quantitative Geoscience	09/2004 – present
Andrew Bell	Chancellor's Fellow in Geophysical Hazards	09/2007 – present
Mireille Huc	PDRA in Statistical Seismology	2000 – 2003
Lun Li	PDRA in Statistical Geophysics	2002 – 2005
John Greenhough	PDRA in Statistical Geophysics	2006 – 2009
Sarah Touati	PhD Student / PDRA in Seismology	2007 – 2010 / 2010 – 2014
Fahad Al-Kindy	PhD Student in Seismology	1999 – 2003

Period when the claimed impact occurred: August 2013 – November 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Operational Earthquake Forecasting (OEF) has been mandated and implemented at a multi-national scale to quantify, communicate and manage risk to society from natural and induced seismicity. Beneficiaries include local populations at risk; Government Agencies responsible for risk assessment, licensing and regulation; Local Authorities; Civil Protection Agencies and Emergency Responders; and Operators of hydrocarbon fields. The New Zealand government instituted a one-year mandatory retrofit programme for reinforced masonry in central New Zealand in the aftermath of the 2016 magnitude 7.8 Kaikoura earthquake, heavily guided by OEF information. The Dutch Government approved gas production plans at Groningen from 2016-2018 with significant operational changes and economic impact, based on operational earthquake forecasts from the field operators. Main's research on quantifying earthquake predictability and forecasting power under uncertainty informed the development of the protocols of OEF and its application.

2. Underpinning research

Before 2000, research on earthquake predictability had centred mainly on the issue of whether reliable precursors existed, and on the possibility of deterministic prediction of the 'time, location and magnitude of future events, within narrow limits, above chance'. Research led by Main since 2000 explored multiple aspects of earthquake predictability and forecasting in a probabilistic framework that accounts for uncertainty. The approach was developed from multiple standpoints, including stochastic modelling, statistical seismology, statistical physics, and rock physics perspectives, and informed the framing of time-dependent operational earthquake forecasting protocols for natural and induced seismicity by direct citation in the International Commission on Earthquake Forecasting (ICEF) report

to the Department of Civil Protection in Italy published in 2011 (see route to impact at the start of section 3).
Research led by Main provided a clear theoretical framework to explain the practical difficulty of accurately predicting individual earthquakes in a near-critical system such as Earth's brittle lithosphere, while allowing a finite degree of low-probability forecasts of likelihoods for a population of events **[**e.g. **3.1]**. This accounted for the practical difficulty of predicting individual earthquakes deterministically, while simultaneously allowing a degree of lower probability forecasting power - above the background rate - that is the basis for OEF. To help quantify the forecasting power in space and time, Huc & Main provided the first estimate of the evolution of the likelihood of triggered events at different epicentral distances and times between events in global earthquake data, notably the discovery of 'anomalous' (non-Gaussian) diffusion of epicentres of triggered events in space and time **[3.2]**.

The research has also established theories and methodologies for the evaluation of earthquake hazard from both background (considered independent) and triggered, (considered dependent) seismicity - in particular allowing for the uncertainty associated with selecting the optimal model for the frequency-magnitude distribution **[3.3]**, and in separating background from triggered seismicity in epidemic-type aftershock sequence models **[3.4]**. The frequency-magnitude distribution is crucial because it controls the likelihood of rare, high-impact, extreme events. The separation of background from triggered events is critical because the background hazard is used to develop building design codes - the front line of defence against earthquakes in urban settings.

The ratio of triggered to background event rate can be used to quantify the improvement in forecasting power during seismic sequences, expressed as a probability gain over the background rate. Both rates are subject to uncertainty caused by the finite and relatively short time window for recorded earthquakes compared to the average recurrence time between large events. Greenhough & Main addressed this issue by quantifying the systematic error in applying different methods to invert for model parameters, while fully accounting for larger uncertainties in the frequency of larger and extreme events **[3.5]**.

Main & Bell also contributed to the design of laboratory experiments and interpretation of their results **[**e.g. **3.6]** to quantify the evolution of seismic energy release as a function of differences in strain rate in rocks undergoing brittle creep deformation, cited by the operators of the Groningen gas field in developing their operational earthquake forecasting model due to time-dependent creep compaction in the reservoir **[5.8]**.

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

[3.1] Main, I.G. & **Al-Kindy**, **F.H.** (2002). Entropy, energy and proximity to criticality in global earthquake populations, ***Geophys. Res. Lett.*** *29*, doi:10.1029/2001GL014078 [43 citations]

[3.2] Huc, M. & **Main, I.G.** (2003). Anomalous stress diffusion in earthquake triggering: correlation length, time dependence, and directionality, ***J. Geophys. Res.*** *108*, 2324, doi: 10.1029/2001JB001645 [56 citations]

[3.3] 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 [31 citations]

[3.4] Touati, S., **Naylor, M.** & **Main, I.G.** (2009). Origin and nonuniversality of the earthquake interevent time distribution, ***Physical Review*** **Letters** *102*, 168501 doi:10.1103/PhysRevLett.102.168501 [62 citations]

[3.5] Greenhough, J. & **Main, I.G.** (2008). A Poisson model for earthquake frequency uncertainties in seismic hazard analysis, ***Geophys. Res. Lett.*** *35*, L19313, doi:10.1029/2008GL035353 [25 citations]

[3.6] Heap, M.J., Baud, P., Meredith, P.G., **Bell, A.F.** & **Main, I.G.** (2009). Time dependent brittle creep in Darley Dale sandstone, ***J. Geophys. Res.*** *114*, B07203, doi: 10.1029/2008JB006212 [203 citations]

The underpinning research listed was published in highly ranked academic journals (Scopus citations as of December 2020 shown above), and supported by peer-reviewed grants. Examples include:

PI **Main, I.G.**, co-Is Atkinson, M., **Bell A.F**, Worton, B., Meredith, P.G., Kilburn, C. (UCL) (2011). 'Exploring Failure FOrecasting in Real Time (EFFORT): from controlled laboratory tests to volcanoes an earthquakes', NERC Grant NE/H02297X/1, GBP612,916.

PI Zapperi, S. (ISC Rome), co-Is **Main, I.G.,** Zaiser, M. (2007). 'Triggering of Instabilities in Materials and Geosystems ' (TRIGS), EU Framework 6, Specific Targeted Research Project (STREP) scheme, NEST-2005-PATH-COM-043386, EURO1,877,189.

PI Ackland, G., co-Is **Main, I.G.** and Lenton T. (University of East Anglia), (2004). 'Novel Approaches to Networks of Interacting Autonomes' (NANIA), EPSRC Initiative on Computing for Complexity, Grant GR/T11753/01, GBP440,057.

Awards: In 2014 Main was awarded the European Union of Geosciences Louis Néel Medal for "sustained and exceptional contributions across a wide range of topics including earthquake scaling, hazard and fluid movements in hydrocarbons reservoirs" and the 2019 American Geophysical Union Ed Lorenz Lecture in 2019 "in recognition of his original contributions to the field of nonlinear geophysics".

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

Routes to Impact: The main route to impact was the ICEF report by Jordan et al. (2011, doi: 10.4401/ag-5350), where Main was one of three principal members of the writing team, and which cites 5 of Main's papers since 2000, including **[3.2]** and **[3.3]**. The ICEF report summarised the state of the art in OEF, and developed protocols for its application in risk assessment and communication. It prompted multi-national developments in public policy and service provision related to earthquake risk reduction that continue to this day. Impact from the research also arises from Main's role as external reviewer to the operators of the Groningen gas field (NAM) in developing their OEF model and to the Dutch Bureau of Mines (SODM) in regulating hydrocarbon production at Groningen, Netherlands.

Impact on Practitioners and Stakeholders:

Italy: The Italian National Geophysical and Volcanological Institute (INGV) operates a live OEF system based on the principles established in the ICEF report. This provided "*statistically reliable and skilful space-time-magnitude forecasts of the largest earthquakes during the complex 2016–2017 Amatrice-Norcia sequence*" in central Italy **[5.1]**. The UK Government assisted the Italian Government in responding to the Norcia-Amatrice sequence via enhanced deployment of UK seismometers one week after the sequence started, led by Margarita Segou of the BGS, with Naylor, McCloskey and Main. The UK Cabinet Office commended our "*contribution to the UK's positive reputation in this area*" and confirmed our "*proactivity was very well received by both the INGV and the Italian Government"* **[5.2]**.

New Zealand: The New Zealand Institute of Geological and Nuclear Sciences (GNS) has continued to issue operational forecasts of earthquake likelihood using the protocols established by the ICEF report. This includes 5 earthquakes since 2014, notably during the magnitude (M) 7.8 Kaikoura sequence in 2016, which affected the Town of Kaikoura itself, and multiple towns in central New Zealand, including on the capital city of Wellington. The OEF lead of the GNS writes "*the New Zealand government instituted a one-year mandatory retrofit programme for reinforced masonry in central New Zealand. The details of the programme were heavily guided by OEF information and the government contributed up to 50% of the retrofit cost.*" **[5.3]**. OEF has been used in New Zealand for: (i) Health and safety assessments for Urban Search and Rescue staff involved in the short-term emergency response; (ii) Assessing the timing and suitability of resettlement or relocation by the Civil

Protection agency; (iii) Assessing and managing the financial impact including adjustment of insurance premiums based on anticipated losses (independently estimated at USD705,000,000 - USD3,500,000,000 in the case of the Kaikoura sequence); (iv) Recovery planning, through mandatory retrofitting of vulnerable buildings, and changes in land use planning and building design codes by Local and National Authorities; (v) Public information throughout the sequence. OEF has also been used to guide timeline decisions for large infrastructure projects, and private companies have used OEF for decisions about planning repair of earthquake damage and for cost-benefit analysis for on-going decision making during recovery time. **[5.3].**

United States: The US Geological Survey (USGS) developed a system that forecasts the probabilities and numbers of aftershocks of different sizes following domestic earthquakes, and applied it during the aftershock sequence of the 2018 Anchorage M7.1 earthquake, the 2019 M6.4-M7.1 Ridgecrest sequence and the 2019-2020 Puerto Rico sequence. There has been wide recognition of OEF by the public, government, media, FEMA (the US Department of Homeland Security - Federal Emergency Management Agency), and others, especially during the Puerto Rico sequence in December 2019. Responding to widespread demands for forecast information, the USGS created a plain-language document that placed the forecast in terms of 'scenarios', plus an analysis to estimate the likely duration of the sequence, published on 30 January 2020 and released in English and Spanish, along with an infographic summary. **[5.4]**. As part of this programme, the USGS received three years of support from USAID Office of Foreign Disaster Assistance to develop a product that has been provided to seismic network operators in several countries (Mexico, Nepal, Myanmar) allowing them to calculate and disseminate aftershock likelihoods. **[5.5]**.

Japan: The ICEF report, and its subsequent approval by the International Association of Seismology and Physics of Earth's Interior influenced the Japanese Cabinet Office decision to suspend deterministic prediction of the Tokai earthquake by the Japanese Meteorological Authority (JMA) in 2018 in favour of an OEF (continuously-updated 'Extra Earthquake Information') service for the Nankai trough. If a period of elevated hazard is detected 'JMA convenes the Nankai Trough Earthquake Assessment Committee for discussions on the expected potential for earthquake occurrence, and issues Earthquake Extra Information to the public via the JMA website and channels such as TV and radio'. **[5.6]**.

Extension to Induced Seismicity: Main's research has underpinned protocols to quantify hazards and manage risks associated with natural gas extraction in the Netherlands, in turn informing decisions by the Dutch Bureau of Mines (SodM), the Netherlands Government, and the field operators NAM **[5.7]**. NAM developed and published a model which "*provides operational forecasts consistent with the observed space–time–magnitude distribution of earthquakes induced by gas production from the Groningen field in the Netherlands…This forecast capability allows reliable assessment of alternative control options to better inform future induced seismic risk management decisions*" [**[5.8]**, citing **[3.6]**]. This has resulted in approval of production, subject to significant managed changes in field operations and a reduction in the associated risk to the public **[5.7]**. In January 2014, the Netherlands Government announced a planned cut in total annual production of natural gas from 53.8 billion cubic metres (bcm) to 40 bcm by 2016, at an estimated cost to Government revenue of EUR1,000,000,000 "*as part of the effort to reduce the danger caused by small but damaging earthquakes*" **[5.9]**. Subsequent cuts, reduced actual production to 24 bcm in October 2016, as confirmed by the Council of State ruling of November 18, 2015. In 2018 production was reduced further to 21.6 bcm of natural gas. **[5.9]**.

Impact on raising public awareness and preparedness: The ICEF report highlighted the critical importance of risk communication during a crisis, and the effective communication of the relevant issues in times of repose, so that practitioners and the general public can act in an informed way during a crisis. Accordingly, the group has also contributed significantly to the public understanding and discussion of earthquake risks through interaction with a range of media outlets in articles or interviews in international media outlets including the

Guardian, Scotsman, commentary in *Nature*, and via Terra Mater's multiple-award-winning documentary *Chasing Quakes* on our work in supporting INGV during the Norcia-Amatrice sequence in 2016-17, featuring Main and Naylor, in December 2017 **[5.10]**.

5. Sources to corroborate the impact

[5.1] Published INGV forecast at https://advances.sciencemag.org/content/3/9/e1701239

[5.2] Letter from the UK Government Cabinet office and associated email from Earthquake Seismologist at British Geological Survey.

[5.3] a) Principal Scientist, *GNS Science* (testimonial letter 05/03/2020); **b)** a contextual article on the scale of insurance losses for the Kaikoura sequence is at https://www.insurancejournal.com/news/international/2016/12/08/434650.htm

[5.4] a) Email and supporting documents from OEF lead for the USGS;
b) https://earthquake.usgs.gov/data/oaf/overview.php

[5.5] Examples of a USGS operational forecast of the likelihood of earthquakes of different sizes are given at **a)** https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511/oaf/commentary (Ridge Crest sequence) and **b)** https://www.usgs.gov/news/magnitude-64-earthquake-puerto-rico (Puerto Rico sequence).

[5.6] a) Earthquake and Volcano Research Centre, *Nagoya University,* (testimonial letter 01/12/2020); **b)** the JMA 'Earthquake Information' website is at: https://www.jma.go.jp/jma/en/Activities/earthquake.html.

[5.7] Senior Specialised Inspector, *State Supervision of Mines.* A letter can be provided on request, confidentially, to verify this statement and provide more detail.

[5.8] The peer-reviewed published operational forecast by NAM, the field operators, citing **[3.6]**, is at doi.org/10.1093/gji/ggy084

[5.9] Reuters report of the announcements and motivation in 2014 and 2018 respectively are at **a)** https://www.reuters.com/article/netherlands-gas-idUSL5N0KR1C820140117 and **b)** https://uk.reuters.com/article/uk-netherlands-groningen-gas/netherlands-to-halt-gas-production-at-groningen-by-2030-idUKKBN1H520E

[5.10]

- **a)** https://www.theguardian.com/science/2016/apr/03/earthquake-prediction-ionised-air-fault-line
- **b)** https://www.theguardian.com/environment/2014/sep/21/scientists-predicting-earthquakes-advance
- **c)** https://www.theguardian.com/world/2015/apr/28/nepal-earthquake-moves-kathmandu-but-everest-height-unchanged-experts
- **d)** https://www.scotsman.com/news/bookies-takes-bets-next-scottish-earthquake-after-rise-1462791
- **e)** https://www.nature.com/news/italian-seismologists-cleared-of-manslaughter-1.16313
- **f)** https://www.sciencealert.com/italy-s-earthquake-scientists-have-been-cleared-for-good
- **g)** https://www.terramater.at/productions/chasing-quakes/