Institution: University College London (UCL)/Birkbeck College

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

Title of case study: Improved seismic hazard mapping by institutions in Italy and Greece

1. Summary of the impact

Birkbeck research on improved mapping of seismic hazards has led to changes in working practices at Italian civil service institutions and the Bank of Greece. In particular, the research has enabled these institutions to make more informed assessments of seismic hazard through the use of five parameters that were not previously considered. Communication of research findings through meetings and websites as part of a new Knowledge Exchange Network has also resulted in improved understanding about earthquake hazard within industry and the financial sector in the UK.

2. Underpinning research

Assessments of earthquake hazard worldwide are mostly underpinned by only around 40 years of instrumental seismicity data. This is a problem, since earthquake recurrence intervals for damaging earthquakes on individual active faults are commonly hundreds to thousands of years. Instrumental seismicity data cannot capture (a) the location of every active fault in a region, (b) the recurrence intervals and natural variability in recurrence intervals for damaging earthquakes on each active fault, and (c) the elapsed time since the last damaging earthquake on each active fault. These variables are essential to calculate the probabilities of damaging earthquakes occurring in a stated time period, and hence to produce probabilistic seismic hazard maps that quantify the geography of both financial and social risk. Furthermore, current methods do not usually include site effects where shaking amplifies/attenuates on soft-sediment/bedrock sites; instead, simple distance attenuation functions for seismic shaking are used.

To address these problems, research within the Department of Earth and Planetary Sciences at Birkbeck involved collaboration with the Italian civil service and the Bank of Greece to enable the calculation and mapping of seismic hazard based on the following five parameters:

(1) Maps of active faults – this parameter identifies all known seismic sources.

(2) Maps of bedrock/sediment that have different site-responses to seismic shaking.

(3) Fault slip-rates and Holocene (15 ± 3 ka) earthquake recurrence intervals (with post-seismic slip subtracted) – this parameter defines how many earthquake shaking events are expected in a given time period using data that are measured over a time period that is known to be long enough to average out temporal earthquake clustering.

(4) Variability in recurrence intervals – this parameter quantifies the variability of recurrence intervals relative to the value averaged over the whole Holocene.

(5) Elapsed time since the last earthquake – this parameter sets the start time for conditional probability calculations for earthquakes on specific faults.

Research between 2008 and 2013 involved (a) field and satellite mapping of active faults to identify all potential seismic sources [1-5]; (b) measurements of geomorphic offsets across faults (usually the offset of the periglacial surface marking the demise of the last glacial maximum 15 ± 3 ka) to gain the slip-rate averaged over multiple seismic cycles [2, 3]; (c) dating the offset surfaces with ^{36}Cl cosmogenic exposure dating to confirm slip-rates; (d) mapping fault kinematics to facilitate calculation of a strain-rate field that quantifies the geography of 15 ka-averaged stress-loading [2]; (e) dating exposed fault surfaces with ^{36}Cl to gain past slip-magnitudes and hence earthquake magnitudes needed to calculate earthquake recurrence intervals; (f) measuring the ^{36}Cl concentration on the immediate top 2 metres of the sub-surface fault plane to gain the residence time in that location and hence the elapsed time since the last surface-faulting (i.e. damaging) earthquake; (g) measuring the surface rupture and afterslip characteristics of a recent earthquake (L'Aquila 2009, M_w 6.3) to calibrate the slip-rate to recurrence interval calculation for older slip [5,

6]; (h) compiling the historical and palaeoseismic database to identify the longest and most geographically complete earthquake record possible [2]; (i) using the earthquake record to calculate Coulomb stress transfer between faults; (j) combining the strain-rate field (loading rate on individual faults), stress transfer results, and elapsed time results to map stress concentration relative to elapsed time across the region; (k) back calculating the stress and elapsed time for all known past earthquakes to test the hypothesis that damaging earthquakes occur preferentially in locations with anomalously long elapsed times and high stress concentrations; and (l) using the results of (k) to produce seismic hazard maps with civil service project partners.

The key Birkbeck researcher was Gerald Roberts (Senior Lecturer and Reader 2008-2012; Professor 2012-present).

3. References to the research

[1] Relationships between fault geometry, slip rate variability and earthquake recurrence in extensional settings, P. A. Cowie, G. P. Roberts, J. M. Bull and F. Visini, *Geophys. J. Int.*, 189, 143-160 (2012) doi:10/n3m

[2] Comparison of earthquake strains over 10^2 and 10^4 year timescales: Insights into variability in the seismic cycle in the central Apennines, Italy, J. P. Faure Walker, G. P. Roberts, P. Sammonds and P. A. Cowie, *J. Geophys. Res.: Solid Earth*, 115, B10418 (2010) doi:10/b9xv34

[3] The Sparta Fault, Southern Greece: From segmentation and tectonic geomorphology to seismic hazard mapping and time dependent probabilities, I. D. Papanikolaou, G. P. Roberts, G. Deligiannakisa, A. Sakellarioua and E. Vassilakis, *Tectonophysics*, 597-598, 85-105 (2013) doi:10/n3n

[4] Shallow subsurface structure of the 2009 April 6 M_w 6.3 L'Aquila earthquake surface rupture at Paganica, investigated with ground-penetrating radar, G. P. Roberts, B. Raithatha, G. Sileo, A. Pizzi, S. Pucci, J. Faure Walker, M. Wilkinson, K. McCaffrey, R. J. Phillips, A. M. Michetti, L. Guerrieri, A. M. Blumetti, E. Vittori, P. A. Cowie, P. Sammonds, P. Galli, P. Boncio, C. Bristow and R. Walters, *Geophys. J. Int.,* 183, 774-790 (2010) doi:10/cdhj4f

[5] Surface faulting of the 6 April 2009 M_w 6.3 L'Aquila earthquake in central Italy, E. Vittori, P. Di Manna, A. M. Blumetti, V. Comerci, L. Guerrieri, E. Esposito, A. M. Michetti, S. Porfido, L. Piccardi, G. P. Roberts, A. Berlusconi, F. Livio, G. Sileo, M. Wilkinson, K. McCaffrey, R. Phillips and P. A. Cowie, *Bull. Seismol. Soc. Am.*, 101, 1507-1530 (2011) doi:10/cjf655

[6] Partitioned postseismic deformation associated with the 2009 M_w 6.3 L'Aquila earthquake surface rupture measured using a terrestrial laser scanner, M. Wilkinson, K. J. W. McCaffrey, G. P. Roberts, P. A. Cowie, R. J. Phillips, A. Michetti, E. Vittori, L. Guerrieri, A. M. Blumetti, A. Bubeck, A. Yates and G. Sileo, *Geophys. Res. Lett.*, 37, L10309 (2010) doi:10/d67wng

References [1], [2] and [3] best indicate the quality of the underpinning research.

Relevant research grants:

(All involve personnel from Italian civil services agencies as project partners involved in mapping seismic hazards.)

(i) NERC Standard Grant NE/I024127/1, Earthquake hazard from ^{36}Cl exposure dating of elapsed time and Coulomb stress transfer, Lead PI Dr. G. P. Roberts, £888,983, 2012-15, including linked awards at Leeds, Ulster and Durham.

(ii) NERC Consortium Grant (NERC NE/J016497/1); Probability, Uncertainty and Risk in the Natural Environment; Dr. Richard Chandler (UCL) £682,000, Prof. Gerald Roberts (Birkbeck) £19,937 (grant total = £1,969,598); 2012-16.

(iii) NERC Urgency Grant NE/H003266/1; A LiDAR and field study of surface rupture and post-seismic slip for the 6th April 2009 L'Aquila Earthquake (M_w 6.3); Dr. K. McCaffrey, Dr. G. P. Roberts and Prof. P. Cowie; £67,184; April 2009-May 2010

(iv) NERC Standard Grant NE/E01545X/1; Testing Theoretical models for Earthquake Clustering using ^{36}Cl Cosmogenic Exposure Dating of Active Normal Faults in Central Italy; Dr. P. Cowie, Dr. G. P. Roberts and Dr. K. McCaffrey; £554,466; 2007-10

4. Details of the impact

Over 90 million people were affected by earthquakes between 2000 and 2012, with more than 800,000 losing their lives. Prior to the research described in section 2, seismic hazard worldwide was usually mapped solely using the locations and frequencies of instrumentally recorded earthquakes, mostly without knowledge of active fault locations. The improved methodology developed by Roberts and collaborators, which uses the five parameters listed in section 2, has been used in 2008-2013 for seismic hazard assessments within institutions in both Greece and Italy, the most seismically active parts of Europe. It has impacted on their working practices and is resulting in more informed calculations of seismic hazard in the two countries.

Change in the Bank of Greece's seismic hazard assessment: The Birkbeck research led in 2013 to a change in the way that the Bank of Greece approaches seismic hazard assessment and calculation of probabilistic seismic risk, following discussions between the bank, Roberts and a Senior Lecturer from the Agricultural University of Athens (who was Roberts' co-author on underpinning research reference [3]). As of July 2013, the Bank of Greece was running a project to facilitate the use of the five parameters listed in section 2 together with the new seismic-hazard mapping methodology that was developed by Roberts. This new method is being implemented for an upcoming new European Union (EU) Directive, known as Solvency II, which codifies and harmonises EU insurance regulations in order to enhance consumer protection. The new directive requires a credible scientific background that offers a probabilistic estimate, something which is found in Roberts' method. Another co-author on the underpinning research has been employed by the Department of Private Insurance Supervision in the Bank of Greece to implement the method and discuss the work with Greek insurance companies. The Agricultural University of Athens Senior Lecturer, who is involved in the project, writes: "The work of Prof. Gerald Roberts has changed the way that the Bank of Greece works in terms of seismic hazard" [A]. In addition, as a result of the work with the Bank of Greece on earthquake insurance risk, the Senior Lecturer has now been elected as a member of the EIOPA (European Insurance and Occupational Pensions Authority) Insurance and Reinsurance Stakeholder Group for a more than 2.5-year mandate as an advisor on earthquake hazard.

Adoption of new tools and methods at the Italian Institute for the Protection and Research of the Environment: The role of the Natural Hazards Unit of the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) is to map, catalogue and risk assess all faults capable of earthquakes for the Italian Civil Protection, which then uses this information to formulate government policy on earthquake risk (e.g. civil defence, infrastructure planning and building regulations). The Head of the Natural Hazards Unit reports that the Birkbeck research has "produced changes to working practices at my institution in terms of new tools and models available to manage seismic hazard and risk, which directly impact on the information we provide to the Italian authorities" [B]. Since 2008, the unit's adoption of methods laid out in the research has changed how it advises the Italian Civil Protection on earthquake hazards and the approaches it uses to collect data and work in the field. The Head of the unit reports: "we now use fault slip-rates, elapsed times since the last earthquake and variability in recurrence intervals in our seismic hazard calculations" and "strain-rates from 15 kyrs [ka] are used to compare against strain-rates from GPS and historical seismicity to gain insights into temporal development of seismicity and hazard" [B]. Insights from the Birkbeck work are used to "guide our approach to research and in our seismic hazard assessments, in that (a) our staff now subtract post-seismic slip from calculations of maximum magnitude from palaeoseismic earthquakes, and (b) use shallow

geophysics to help assess fault slip-rates" [B]. These impacts were enabled through research collaborations between Birkbeck and ISPRA. The research is also having an impact on public understanding, with the Head of the Natural Hazards Unit reporting that he has used the research insights to "improve communication with the public about earthquake risks through a series of publicly available videos" [B].

Adoption of new techniques at the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV): The INGV is an Italian civil service institution that helps to guide government policy on seismic hazards. It conducts 24-hour countrywide seismic surveillance, and early warning and forecast activities. Since 2009, the Birkbeck research has impacted upon working practices at the INGV. For example, an Earthquake Scientist at the INGV, who works on improving seismic hazard mapping methodology, reports: "For the last 4 years, my work has been influenced by that of Professor Gerald Roberts. His work has had an impact on mine, changing the way I have been working, because he has convinced myself and others that faults need to be included in seismic hazard assessments so that we can use their slip-rates, earthquake recurrence intervals, variability in recurrence intervals and elapsed time since the last earthquake to calculate and map earthquake probabilities. Before his work, these parameters were not used" [C]. A Senior Researcher at the INGV also reports that the Birkbeck research is "having [an impact] on my work and in my institution" [D]. These impacts on the INGV took place following research collaborations between the institution and Birkbeck.

The ultimate benefit of the research to the Greek and Italian organisations above is that they have greater understanding and decreased uncertainty concerning the locations, numbers and behaviour of active faults that are the sources of devastating earthquakes.

Improved understanding of seismic hazard within industry and the financial sector: Birkbeck research findings are also being communicated, through the new PURE (Probability, Uncertainty and Risk in the Environment) Knowledge Exchange Network and Research Programme, funded by NERC, to industrial partners including Narec Capital Ltd., Hiscox Ltd., Aon Benfield, EuroTempest, Arup Group, Lighthill Risk Network, and Met Office. PURE, which is being coordinated through UCL's Institute of Risk and Disaster Reduction, will help the UK Government prepare for natural hazards and disaster situations, and will help insurance industries meet the requirements and risk management standards of the new Solvency II EU Directive. In particular, through the PURE network blog, websites and meetings, Roberts is involved in communicating to industrial partners the hazards associated with devastating earthquakes, elapsed time science, and the effects of stress transfer between faults, improving their understanding and knowledge of these issues [E].

5. Sources to corroborate the impact

[A] Supporting letter from Senior Lecturer, Agricultural University of Athens – corroborates impact on approach to seismic hazard assessment at the Bank of Greece. Available on request.

[B] Supporting letter from Head of Natural Hazards Unit, ISPRA – corroborates impact on working practices at ISPRA. Available on request.

[C] Supporting letter from Earthquake Scientist, INGV – corroborates impact on working practices at INGV. Available on request.

[D] Supporting letter from Senior Researcher, INGV – corroborates impact on working practices at INGV. Available on request.

[E] The Director of the Financial Services Knowledge Transfer Network can be contacted to corroborate the claim that Birkbeck research findings have been communicated to industrial partners through the PURE programme, and that this communication has led to improved understanding of issues relating to seismic hazard. Contact details provided separately.