What Works and Does not Work in the Science and Social Science of Earthquake Vulnerability?

Report of an International Workshop held in the
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This Workshop, supported by Shell, Chun Wo Development Holdings (Hong Kong), and the National Centre for Earth Observation, was held in response to NERC's Action Plan: *Increasing resilience through improved hazard forecasting and take-up of scientific advice in earthquake-prone and volcanic regions*. Over fifty scientists, social scientists, and engineers attended the Workshop, bringing extensive experience of earthquake risk from Greece, India, Italy, Iran, Pakistan, Turkey, and the USA. The list of the international participants is given in Appendix B, and electronic versions of their presentations can be found on the Workshop website.

The participants considered earthquake resilience in a global context, but were also aware of the constraints (Rees) associated with NERC's Programme in Increasing Resilience to Natural Hazards, particularly the limited budget and time frame. Their discussion therefore was also conditioned by the following questions: *(i)* Which areas in UK science can make the greatest impact in increasing resilience and reducing uncertainty about risk? *(ii)* What practical outcomes can be achieved within the financial and temporal constraints of this programme?

The following recommendations arose from the two days of discussion:

- The overwhelming priority, when considering resilience to earthquakes, is the risk to human life in the developing world. (Section 1)
- The greatest risk to human life from earthquakes lies not at plate boundaries, but in the continental interiors, where growing populations are exposed to earthquake risk from distributed networks of faults that are poorly characterized. (Section 2)
- The unifying themes across all earthquake-prone societies are that reliable knowledge of the processes of earthquake generation, underpinned by basic science, is fundamental to increased resilience, and the transmission of that knowledge to individuals, communities, and governments, is a prerequisite for effective action. (Section 3, Section 4)
- The Increasing Resilience to Natural Hazards Programme is likely to make its greatest impact on earthquake risk by focusing on the risk to human life in those countries where the capabilities of the earthquake science community need to be developed, and there is significant uncertainty in our knowledge of the earthquake hazard. (Section 1)
- Problems of uptake of scientific advice are context-specific, but the UK social science community has relevant expertise in the development and application of appropriate methodologies in both developed, and developing, world settings. New partnerships will need to be forged between social scientists and earthquake scientists. (Section 3)
- Improving knowledge of seismic risk rests on the use of a wide range of geological and geophysical skills to identify the distribution of hazard, which is often poorly known in the countries most at risk. The INRH Programme should seek to export the UK's expertise in these areas to the scientific communities of those countries. (Section 4)
- Training of young indigenous researchers in the relevant scientific and social-scientific disciplines is essential if this Programme is to provide a lasting legacy in the countries at risk. (Section 4)
- NERC should critically reappraise the scientific goals defined in its current Theme Action Plan, as they relate to earthquake risk. The scientific scope of that Plan is limited, and fails to address the most pressing problems concerning earthquake hazard and risk in the countries most exposed to heavy loss of life in earthquakes. (Section 5)

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1. Resilience to Earthquakes: Global Variability

A stark divide separates the developed world, in which societies are highly resilient to earthquakes, from the developing world, in which even relatively small earthquakes cause large death tolls and have huge economic impacts (Figure 1 & Figure 2; Lay, Calais). The past century's earthquakes tell us that the INRH Programme enters an arena in which "The rich pay, and the poor die" (Bilham). Furthermore, the earthquake risk in Turkey, Iran, Central Asia, Pakistan, India and China is rapidly becoming more acute as people migrate towards mega-cities, whose populations are likely to increase by 2 billion in the next two decades (Tucker).

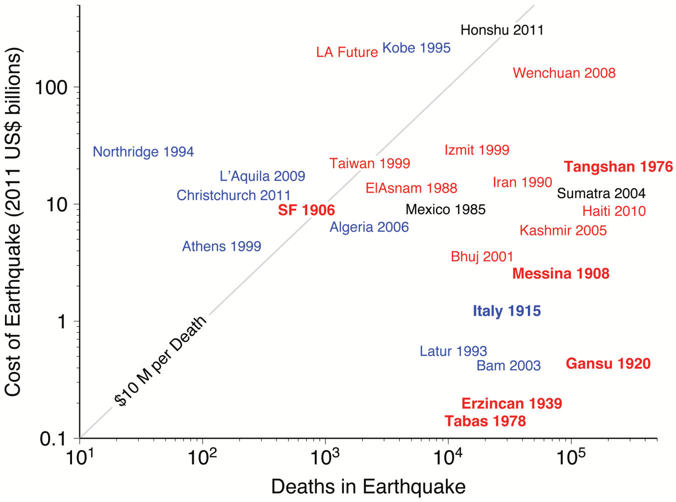

Figure 1: Cost of damage (in $US billions, adjusted for inflation) *vs.* loss of life for major earthquakes of the past 25 years. Selected earthquakes from earlier in the 20th century are labelled in bold. Black type indicates great earthquakes ($M_w > 8$), red type indicates earthquakes $7 < M_w < 8$, and blue indicates $M_w < 7$, from NOAA Significant Earthquake Database (http://www.ngdc.noaa.gov/hazard/earthqk.shtml, see also Table A.2).

It is extremely unlikely that NERC's INRH Programme could significantly increase resilience in the developed world, because its financial envelope is tiny in comparison with the sums expended annually on the assessment and mitigation of earthquake risk[2]. As a result of this investment death tolls in the developed world, while nevertheless tragic, are relatively low. For example, in the recent Christchurch, New Zealand, earthquake, fewer than 0.1% of the population affected by shaking of intensity VIII or greater were killed, and the M_w9 Tōhoku earthquake exposed over 6 million people to shaking of intensity VIII+ [1], of whom approximately ∼ 0.4% died or are still missing, mostly in the tsunami.

Those figures are in striking contrast to death rates cause by earthquakes in the developing world, which often exceed 5% and, as in the 2003, Bam, Iran earthquake, can be as high as 30%. Furthermore, much of the seismic hazard in the developing world arises in the continental interiors, where the problem is intrinsically more complex than at plate boundaries (Iyengar, Selvaggi, Talebian, and see Section 2, below).

For these reasons, the participants in the Workshop emphasized that the overwhelming priority, when considering resilience to earthquakes, is the risk to human life in the developing world.

Although the principal benefits of the INRH Programme, within its lifetime, are likely to be humanitarian, the improved scientific knowledge will also have financial implications. Increasing population density means that the cost of earthquakes is rising steeply. As Figure 1 shows, damage caused by earthquakes in the past couple of decades cost significantly more than in earthquakes of similar magnitudes within the same country earlier in the twentieth century (in some cases by more than a factor of 10 – all costs in Figure 1 are in 2011 $US). The rate of economic development in India and China is further escalating the structural capital at risk. Such countries represent a growth area in the insurance markets, so reduction of the uncertainty in risk would have significant economic implications in the medium term (Coburn).

2. Distributions of Earthquake Risk

Devastating earthquakes take place in two principal settings: on plate boundaries, and on diffuse networks of faults within continental interiors. The plate boundaries are narrow fault zones, whose locations are precisely known. The networks of faults within the continents are hundreds or thousands

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[2] The USA National Earthquake Hazards Reduction Plan has run for 35 years, and is currently funded at $120M per year; Japanese expenditure is of comparable magnitude.

of kilometres in width and contain hundreds of separate faults, many of whose locations and seismic potential are poorly known [2, 3]. During the past 120 years, about 130 earthquakes took place in which 1000 or more people died (Figure 2 and Table A.1). Of these, about 30 took place on plate boundaries, causing 800,000 deaths. Over that interval, earthquakes in the continental interiors caused the deaths of at least 1,400,000.

Figure 2 carries several crucial implications for the INRH Programme. *(i)* Many more people die in earthquakes in the continental interiors than in earthquakes on plate boundaries. *(ii)* Most of these deaths occur in earthquakes of M_w 7–8, which have typical repeat times of a few hundred to a few thousand years; it follows that the faults which generated the devastating earthquakes in the continental interiors during the past century represent only a small fraction of the total number of faults upon which future similar earthquakes are accumulating. *(iii)* We do not know where most of those faults are. The majority of the devastating earthquakes in the continental interiors take place on faults whose existence was previously unknown, or whose threat was not anticipated. Recent examples include earthquakes in Bam, Iran, in 2003 (30,000 deaths), Muzzafarabad, Pakistan, 2005 (75,000), and Wenchuan, China, 2008 (70,000). *(iv)* The severity of this threat is increasing rapidly as millions of people every year migrate into vulnerable mega-cities [4–6].

For these reasons, participants in the Workshop argued that the most significant impact of NERC science upon resilience to earthquakes would be to improve knowledge of the seismic hazard posed by the distributed faulting in the continental interiors. Large populations in developing countries across the Middle East and Asia are exposed to this poorly understood hazard, and they need to develop the capabilities of their communities to meet this challenge.

Action based on this knowledge has the potential to make significant impacts on the risk to life in many countries where earthquakes as small as M_w 7 frequently cause tens of thousands of deaths (Figure 2, and Figure A.1). This knowledge will also pay dividends in plate-boundary settings; for example, there are striking parallels between the 2003, Bam, Iran earthquake and the 2010/11 Canterbury, New Zealand and 2010 Haïti earthquakes.

3. Application of knowledge

The political and social problems associated with earthquake risk are highly context-specific; the challenges of getting scientific advice or conclusions adopted vary widely from country to country. Even the simple question of whether a “top-down” or a “bottom-up” approach is more effective has multiple answers. For example, in places such as Nepal and Indonesia highly effective work takes place with local communities and NGOs, whereas in Iran there are no NGOs and engagement with government agencies is inevitable (Tucker). In many environments, the key players may be neither the local communities nor the government; the important decision-makers may, for example, be those who drive the economic growth of cities. The success or failure of engagement often depends upon the personalities of the people one is dealing with. In some countries, the main killer is lack of an effective construction code; in others, it is circumvention of perfectly adequate construction codes (Erdik, Lodi, Spence). Often, societies have highly unrealistic expectations of what scientists can deliver [7, 8].

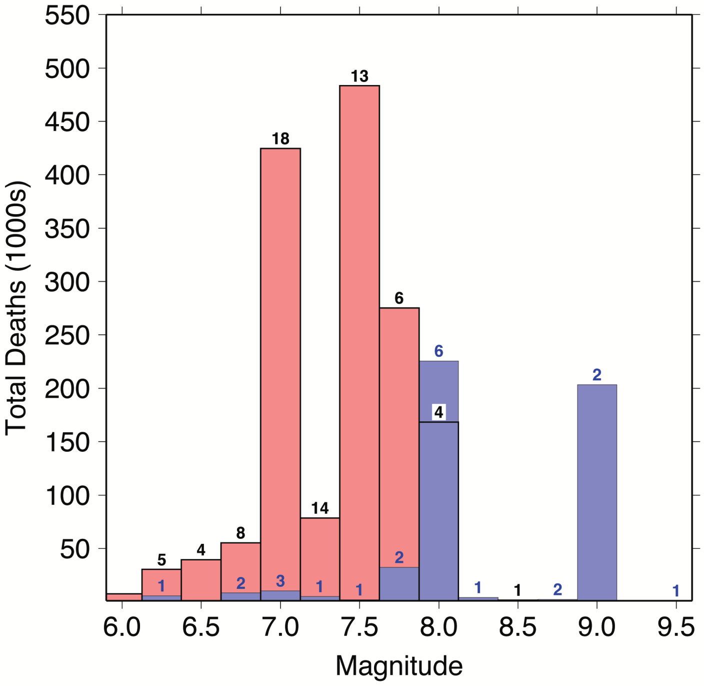

Figure 2: The distribution of deaths among earthquakes in continental interiors (red bars) and on plate boundaries (blue bars). See Appendix A for further discussion.

Agreement among the participants centred around the following points:

- Devastating earthquakes in a particular country often occur over areas that are hundreds of kilometres wide, affecting large populations in a wide variety of risk environments. Some degree of governmental involvement is required if widespread mitigation methods are to be put in place. However, key decision-makers are often indifferent to evidence-based advice.
- Commonly, a sophisticated local understanding already exists of the barriers to converting scientific and engineering knowledge into effective solutions. Therefore, there must be clear identification of the ways in which UK-based scientists and social scientists can augment indigenous efforts.
- Lessons about earthquake risk, and response to it, often are not exported by the communities that learn them. However, there are nascent programmes to disseminate this knowledge, and they would benefit from a coherent framework for the uptake of scientific information.

Participants in the Workshop identified underlying themes that would derive great benefit from a multi-national approach, and which can only be fully addressed by looking across the entire spectrum of earthquake-related problems, and of the societies in which they are embedded.

- A toolkit of approaches has been developed and successfully applied in enabling science to inform policy and action in other problem areas (Young). How can this experience best be translated into the earthquake arena?
- Earthquake science is young. What are the pathways to impact for a science that is still evolving? How can societies be persuaded to act on knowledge whilst it is still being generated? There are clear parallels here with many other areas of NERC's activities, particularly LWEC.
- How do we design a feed-back loop that allows our learning about the *applicability* of the scientific knowledge to influence the evolution of scientific priorities during the programme?

4. UK role in earthquake science

Participants from countries at high risk from earthquakes all made the same two points. First, the involvement of foreign scientists improves understanding of local earthquake problems through insights gained from other tectonic settings. Secondly, the conclusions that individual scientists reach with respect to earthquake risk carry more influence within their own countries when those scientists are recognized as being part of the international community.

The fundamental uncertainty in earthquake risk in the continental interiors lies in where the hazards are accumulating. The challenge is to measure the rates of strain, and then to identify the faults on which that strain will be released. This task is significantly more difficult than at the plate boundaries, because the areas affected are millions of square kilometres in extent, and logistics are frequently challenging. Success in this enterprise depends on bringing a wide range of techniques in geodesy, seismology, geomorphology, geochronology, and geology to the problem. The UK has a long track record of using these multi-disciplinary skills in partnership with colleagues from many parts of the world. Recent high-profile examples of this approach include the quantification of the tsunami hazard in the eastern Mediterranean [9], and the recognition of a blind thrust fault in the centre of Tehran (Jackson).

There is an urgent need in many countries to generate a critical mass of researchers in the area of earthquake risk. Significant advances have taken place in our ability to identify the traces of active faulting during the past decade [10], and the INRH Programme offers an opportunity to disseminate this knowledge into the countries where it is needed. Research training through an international programme would contribute immensely towards that goal. Participants in the Workshop urged that training of young indigenous researchers in the relevant scientific and social-scientific disciplines is essential if this Programme is to provide a lasting legacy in the countries at risk (Bilham).

5. What Doesn't Work

One aim of this Workshop was to illuminate practices that have been unsuccessful when applied to the problems of earthquake risk. The points below are widely understood by the international scientific community, but some may have been overlooked during development of the Theme Action Plan.

Don't fight the last war. Media and political pressures often over-emphasize the significance of a current tragic event. It is not uncommon for funding agencies to respond to those pressures by diverting funds away from long-term basic science, while the spotlight is upon such events. The recent unexpected earthquakes in New Zealand and Japan emphasize the limitations of this approach. Looking backwards is a poor way of predicting what will happen next when dealing with rare, high-intensity events. Having said that, it is worth noting that there 40 nuclear reactors operating or under construction in China, one of the areas at greatest risk from distributed faulting (Figure 1, and see Appendix A).

Don't focus too narrowly. International participants who read the Theme Action Plan were surprised by its emphasis on a very narrow area of earthquake science. All participants in the Workshop were adamant that the science and social science required to make a significant impact on earthquake risk are broad in their scope. The fundamental route to increasing societies' resilience to earthquakes is through improving basic knowledge about earthquake phenomena and advancing understanding of earthquake generation processes. Indeed, this philosophy underpins the entire US National Earthquake Hazard Reduction Programme, and should underpin NERC's programme.

Don't confuse humanitarian and scientific priorities. To take a topical example: there is little doubt that the city of Padang, Sumatra, is exposed to an enormous tsunami risk because it sits in a gap between recent great earthquakes. Scientists correctly identified the the tsunami hazard before the 2004 earthquake (*e.g.* [11]), and have refined the information as far as possible since then. The urgent need now lies outside the realm of scientific enquiry: large-scale engineering is necessary to build tsunami refuges for the 600,000 people at risk (Tucker).

Don't apply the wrong solutions. On the plate boundaries, the location of the hazard is well known and the greatest uncertainty lies in when the earthquakes will occur. In many parts of the continental interiors, however, we do not even know where the hazards lie. Participants in the Workshop warned that slavish application of a model based on plate boundaries around the Pacific rim to earthquake hazard in the continental interiors is not merely unhelpful, but can be positively dangerous. At the plate boundaries, a parsimonious approach is justified: identification of one, or a few, major faults is usually sufficient to identify the major hazards. Such an approach, when applied to the continental interiors, overestimates the hazard associated with the identified faults and neglects the hazard elsewhere. Anyone who doubts this point needs only to read the accounts of devastating earthquakes in the past two millennia in southern Europe and the Middle East [12–14], and attempt to assign them with certainty to faults of known location.

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A Appendix A

Figure A.1 shows the locations of the earthquakes summarized in Figure 2. In this figure, earthquakes not occurring on plate boundaries are inscribed within a black circle. Some earthquakes, a recent notable example is the 2010 Haïti earthquake, are commonly thought of as plate boundary earthquakes, but the key argument in Section 2 is that the greatest uncertainty in seismic risk lies in places where the release of strain could occur on any one of a number of faults. The fault that slipped the 2010 Haïti earthquake is *(i)* only one of several large faults in the region and *(ii)* is not the plate boundary. Similar arguments apply to earthquakes along the Himalaya; the large thrust faults of this region are sometimes referred to as a plate boundary but, again, the fact that the locations and seismic potentials of these faults are poorly known is the important issue.

In Table 1, the earthquakes that took place on a plate boundary (all of those causing 1000 or more deaths occurred on subduction zone faults) are labelled "PB", those in continental interiors are labelled "CI". Locations and origin times are taken from the NOAA Significant Earthquake Database (http://www.ngdc.noaa.gov/hazard/earthqk.shtml). Except as indicated, magnitudes are assigned as follows: if the earthquake is in the catalogue of Engdahl and Villaseñor, (*International Geophysics* **81** 665-690, International Handbook of Earthquake and Engineering Seismology), their magnitude is used; failing that, the magnitude given by NOAA is used; failing that, the magnitude from the USGS website are used. Other sources for magnitudes are given in the caption to Table 1. Dashes in the Table indicate unresolved depths or magnitudes.

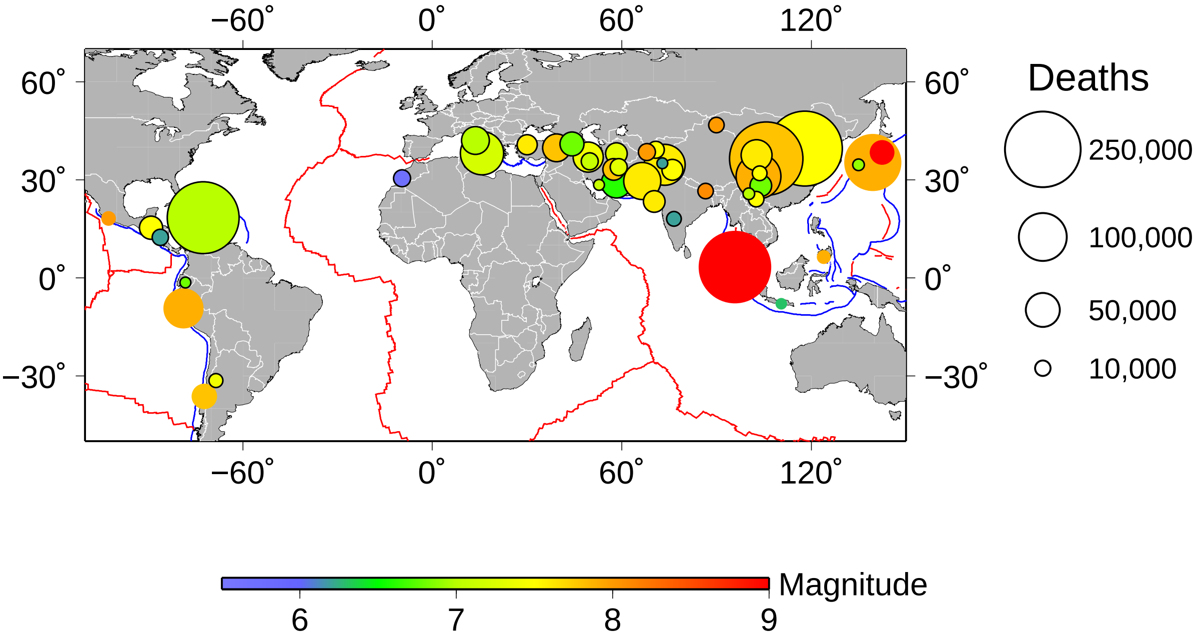

Figure A.1: Distribution and scale of earthquake-related deaths for 1900-2011. Circles show earthquakes with more than 10,000 fatalities; the area of the circle is proportional to the number of deaths and the colour to the earthquake magnitude. Earthquakes represented by circles with black rims did not occur on plate boundaries.

Table A.1:

Year	Month	Day	Hour	Minute	Latitude	Longitude	Depth (km)	M_w	Deaths		Location
1976	7	27	19	42	39.57	117.98	23	7.5	242000	CI	CHINA NE TANGSHAN
2010	1	12	21	53	18.457	-72.533	13	7.0	222570	CI	HAITI PORT-AU-PRINCE
1920	12	16	12	5	36.7	104.9	17	7.8	200000	CI	CHINA GANSU PROVINCE, SHANXI PROVINCE
2004	12	26	0	58	3.295	95.982	30	9.1	175827	PB	INDONESIA SUMATRA OFF WEST COAST
1923	9	1	2	58	35.1	139.5	40	7.9	142807	PB	JAPAN TOKYO, YOKOHAMA
2008	5	12	6	28	31.002	103.322	19	7.9	87652	CI	CHINA SICHUAN PROVINCE
2005	10	8	3	50	34.539	73.588	26	7.6	86000	CI	PAKISTAN MUZAFFARABAD, URI, ANANTNAG,
1908	12	28	4	20	38.183	15.683	10	7.1	82000	CI	ITALY MESSINA, SICILY, CALABRIA
1970	5	31	20	23	-9.2	-78.8	43	7.9	66794	PB	PERU NORTHERN, PISCO, CHICLAYO
1935	5	30	21	32	29.5	66.8	33	8.1	60000	CI	PAKISTAN QUETTA
1927	5	22	22	32	36.75	102	27	7.6	40912	CI	CHINA GANSU PROVINCE
1990	6	20	21	0	36.957	49.409	19	7.4	40000	CI	IRAN RASHT, QAZVIN, ZANJAN, RUDBAR, M
1939	12	26	23	57	39.8	39.5	27	7.7	32700	CI	TURKEY ERZINCAN
2003	12	26	1	56	28.995	58.311	10	6.6	31000	CI	IRAN SOUTHEASTERN BAM, BARAVAT
1939	1	25	3	32	-36.25	-72.25	60	7.7	30000	PB	CHILE CHILLAN
1972	4	10	2	6	28.4	52.8	11	6.9	30000	CI	IRAN QIR,KARZIN, JAHROM, FIRUZABAD
1915	1	13	6	52	42	13.5	10	6.9	29978	CI	ITALY MARSICA, AVEZZANO, ABRUZZI
2011	3	11	5	46	38.322	142.369	32	9.0	27581	PB	JAPAN HONSHU
1988	12	7	7	41	40.987	44.185	5	6.8	25000	CI	ARMENIA LENINAKAN, SPITAK, KIROVAKAN
1976	2	4	9	1	15.324	-89.101	5	7.5	23000	CI	GUATEMALA CHIMALTENANGO, GUATEMALA CIT
2001	1	26	3	16	23.419	70.232	16	7.7	20005	CI	INDIA GUJARAT BHUJ, AHMADABAD, RAJOK
1974	5	10	19	25	28.24	104.01	11	6.8	20000	CI	CHINA YUNNAN AND SICHUAN PROVINCES, CH
1978	9	16	15	35	33.386	57.434	33	7.4	20000	CI	IRAN TABAS
1948	10	5	20	12	37.95	58.32	18	7.2	19800	CI	TURKMENISTAN ASHKHABAD
1905	4	4	0	50	33	76	25	7.8	19000	CI	INDIA KANGRA
1999	8	17	0	1	40.748	29.864	17	7.6	17118	CI	TURKEY ISTANBUL, KOCAELI, SAKARYA
1960	2	29	23	40	30.45	-9.62	33	5.7	13100	CI	MOROCCO AGADIR
1962	9	1	19	20	35.63	49.87	27	6.9	12225	CI	IRAN BUYIN-ZARA
1907	10	21	4	23	38.5	67.9	35	7.2	12000	CI	TAJIKISTAN KARATAG
1993	9	29	22	25	18.066	76.451	7	6.2	11000	CI	INDIA LATUR-OSMANABAD, KILLARI
1934	1	15	8	43	26.5	86.5	33	8.1	10600	CI	INDIA BIHAR; NEPAL
1968	8	31	10	47	34	59	13	7.2	10488	CI	IRAN DASHT-E-BAYAZ
1931	8	10	21	18	47.1	89.8	25	8.0	10000	CI	CHINA XINJIANG WEIWUER ZIZHIQU PROVINC
1970	1	4	17	0	24.1	102.5	31	7.2	10000	CI	CHINA YUNNAN PROVINCE; VIETNAM HANOI
1972	12	23	6	29	12.4	-86.1	5	6.2	10000	CI	NICARAGUA MANAGUA
1985	9	19	13	17	18.19	-102.533	28	8.0	9500	PB	MEXICO MICHOACAN MEXICO CITY
1933	8	25	7	50	31.9	103.4	-	7.3	9300	CI	CHINA SICHUAN PROVINCE

Table A.1:

Year	Month	Day	Hour	Minute	Latitude	Longitude	Depth (km)	M_w	Deaths		Location
1944	1	15	23	49	-31.5	-68.5	50	7.1	8000	CI	ARGENTINA SAN JUAN PROVINCE
1949	8	5	19	8	-1.5	-78.2	60	6.8	6000	PB	ECUADOR
2006	5	26	22	53	-7.961	110.446	13	6.3	5749	PB	INDONESIA JAVA BANTUL, YOGYAKARTA
1995	1	16	20	46	34.583	135.018	22	6.9	5502	PB	JAPAN SW HONSHU KOBE, AWAJI-SHIMA, N
1909	1	23	2	48	33	50	33	7.3	5500	CI	IRAN SILAKOR
1974	12	28	12	11	35.1	72.9	22	6.2	5300	CI	PAKISTAN BALAKOT, PATAN
1976	6	25	19	18	-4.6	140.09	33	7.2	5150	PB	INDONESIA NEW GUINEA IRIAN JAYA
1948	6	28	7	13	36.5	136	20	7.0	5131	CI	JAPAN FUKUI
1925	3	16	14	42	25.7	100.4	26	7.0	5000	CI	CHINA YUNNAN PROVINCE TALIFU
1976	11	24	12	22	39.12	44.03	36	7.0	5000	CI	TURKEY MURADIYE
1980	10	10	12	25	36.195	1.354	10	7.1	5000	CI	ALGERIA NORTHERN
1902	12	16	5	7	40.8	72.3	9	6.4	4880	CI	UZBEKISTAN ANDIZHAN
1923	3	24	12	40	31.5	101	13	7.2	4800	CI	CHINA SICHUAN PROVINCE
1980	11	23	18	34	40.914	15.366	20	6.9	4689	CI	ITALY AVELLINO, POTENZA, CASERTA, NAP
1943	11	26	22	20	41	33.7	33	7.5	4020	CI	TURKEY LADIK
1906	8	17	0	40	-33	-72	25	8.2	4000	PB	CHILE SOUTH CENTRAL
1914	10	3	22	6	37.82	30.27	-	7.1	4000	CI	TURKEY BURDUR, KILINC, KECIBORLU, ISPA
1942	11	26	22	20	40.5	34	-	7.3	4000	CI	TURKEY HAVZA,LADIK
1945	11	27	21	56	24.5	63	-	8	4000	PB	PAKISTAN MAKRAN COAST
1998	5	30	6	22	37.106	70.11	33	6.6	4000	CI	AFGHANISTAN BADAKHSHAN, TAKHAR
1929	5	1	15	37	37.8	57.6	50	7.1	3800	CI	IRAN KOPET-DAGH
1903	4	28	23	46	39.1	42.5	-	5.8	3560	CI	TURKEY MALAZGIRT
1949	7	10	3	53	39.2	70.8	16	7.6	3500	CI	TAJIKISTAN
1935	4	20	22	1	24.3	120.8	-	7.1	3276	CI	TAIWAN MIALOI
1912	8	9	1	29	40.5	27.2	60	7.6	3000	CI	TURKEY MARMARA SEA
1951	2	18	0	0	-9.3	147.1	-	-	3000	PB	PAPUA NEW GUINEA
1969	7	25	22	49	22.317	111.8	5	5.9	3000	CI	CHINA GUANGDONG PROVINCE YANGJIANG C
1981	6	11	7	24	29.913	57.715	33	6.6	3000	CI	IRAN SE GOLBAFT
1981	7	28	17	22	30.013	57.794	33	7.3	3000	CI	IRAN SE, KERMAN
1927	3	7	9	27	35.6	135.1	10	7.1	2956	PB	JAPAN HONSHU SW
1931	4	27	16	50	39.2	46	22	5.7	2890	CI	ARMENIA ZANGEZUR, NAKHITCHEVAN
1982	12	13	9	12	14.701	44.379	5	6.2	2800	CI	YEMEN DHAMAR
1935	7	16	16	18	24.6	120.8	30	6.5	2746	CI	TAIWAN XIINZHU
1917	12	26	4	30	14.6	-90.6	-	5.6^a	2650	CI	GUATEMALA GUATEMALA CITY
1902	8	22	3	0	39.88	76.2	30	7.7	2500	CI	CHINA XINJIANG, TURKESTAN
1931	3	31	16	2	13.2	-85.7	-	6.0	2450	CI	NICARAGUA MANAGUA
1990	7	16	7	26	15.679	121.172	25	7.7	2412	PB	PHILIPPINES BAGUIO, CABANATUAN, DAGUP

Table A.1:

Year	Month	Day	Hour	Minute	Latitude	Longitude	Depth (km)	M_w	Deaths		Location
1966	8	19	12	22	39.2	41.6	24	5.8	2394	CI	TURKEY VARTO
1944	2	1	3	23	41.4	32.7	33	7.2	2381	CI	TURKEY
1998	2	4	14	33	37.075	70.089	33	5.9	2323	CI	AFGHANISTAN ROSTAQ; TAJIKISTAN DUSHA
1975	9	6	9	20	38.474	40.723	26	6.7	2311	CI	TURKEY LICE
1945	1	12	18	38	34.7	137.2	-	6.8	2306	PB	JAPAN HONSHU S
1999	9	20	17	47	23.772	120.982	33	7.7	2297	CI	TAIWAN NANTOU, TAICHUNG, TAIZHONG
2003	5	21	18	44	36.964	3.634	12	6.8	2266	CI	ALGERIA ALGIERS, BOUMERDES, REGHIA, TH
2010	4	13	23	49	33.165	96.548	17	6.9	2220	CI	CHINA QINGHAI PROVINCE YUSHU
1923	5	25	22	21	35.2	59.2	-	5.7	2200	CI	IRAN TURBAT-HAKLARI
1902	4	19	2	23	14	-91	33	7.5	2000	PB	GUATEMALA QUEZALTENANGO, SAN MARCOS
1918	2	13	6	7	23.5	117.2	23	7.2	2000	CI	CHINA GUANGDONG PROVINCE
1954	6	10	0	0	36	66	-	-	2000	CI	AFGHANISTAN NORTHERN
1991	10	19	21	23	30.78	78.774	10	6.8	2000	CI	INDIA CHAMOLI, UTTARKASHI, NEW DELHI,
1995	5	27	13	3	52.629	142.827	11	7.1	1989	PB	RUSSIA SAKHALIN IS NEFTEGORSK, OKHA,
1917	7	30	23	54	28	104	33	7.3	1800	CI	CHINA YUNNAN PROVINCE
1910	4	13	6	40	9.8	-84	-	5.7^a	1750	PB	COSTA RICA CARTAGO
1997	5	10	7	57	33.825	59.809	10	7.2	1728	CI	IRAN BIRJAND, GHAEN
1903	4	19	0	0	39.1	42.4	-	-	1700	CI	TURKEY
1977	3	4	19	21	45.77	26.76	94	7.5	1581	CI	ROMANIA BUCHAREST
1950	8	15	14	9	28.5	96.5	33	8.6	1530	CI	INDIA-CHINA
1917	1	20	23	11	-7	116	-	-	1500	PB	INDONESIA BALI
1930	7	23	0	9	41.1	15.4	7	6.5	1430	CI	ITALY IRPINIA
1920	9	7	5	55	44.3	10.3	10	-	1400	CI	ITALY CARRARA,GARFAGNANA
1943	9	10	8	37	35.3	133.9	10	7.0	1400	CI	JAPAN HONSHU S
1946	12	20	19	19	33	135.6	20	8.1	1362	PB	JAPAN HONSHU S COAST
1930	5	6	22	34	38.1	44.7	30	7.1	1360	CI	IRAN SALMAS
1983	10	30	4	12	40.33	42.187	12	6.6	1342	CI	TURKEY ERZURUM, KARS, KHORASAN, PASINL
2005	3	28	16	9	2.085	97.108	30	8.7	1303	PB	INDONESIA SUMATERA SW
1906	3	16	22	42	23.6	120.5	-	6.8	1258	CI	TAIWAN JIAYI
1954	9	9	1	4	36.283	1.467	-	6.7	1243	CI	ALGERIA ORLEANSVILLE
1944	12	7	4	35	34	137.1	30	8.1	1223	PB	JAPAN OFF SOUTHEAST COAST KII PENINSUL
1941	1	11	8	32	16.4	43.5	-	5.9^b	1200	CI	YEMEN RAZIH
1957	12	13	1	45	34.3	47.8	-	6.8	1200	CI	IRAN FARSINAJ
1999	1	25	18	19	4.461	-75.724	17	6.2	1185	CI	COLOMBIA ARMENIA, CALARCA, PEREIRA, CA
2009	9	30	10	16	-0.72	99.867	81	7.5	1117	CI	INDONESIA SUMATRA PADANG
1951	5	6	23	8	13	-87.8	100	-	1100	PB	EL SALVADOR JUCUAPA

Table A.1:

Year	Month	Day	Hour	Minute	Latitude	Longitude	Depth (km)	M_w	Deaths		Location
1957	7	2	0	42	36.1	52.7	14	7.1	1100	CI	IRAN HAZANDERAN, ABEGARM
1986	10	10	17	49	13.827	-89.118	7	5.7	1100	CI	EL SALVADOR SAN SALVADOR
1997	2	28	12	57	38.075	48.05	10	6.1	1100	CI	IRAN ARDABIL
1988	8	20	23	9	26.755	86.616	57	6.9	1091	CI	NEPAL-INDIA KATHMANDU, BIHAR
1970	3	28	21	2	39.2	29.5	20	7.4	1086	CI	TURKEY GEDIZ
1932	5	20	19	16	36.6	53.4	12	-	1070	CI	IRAN TORBET-I-KHEYDARLY
1953	3	18	19	6	40	27.5	-	7.2	1070	CI	TURKEY YENICE, ONON
1963	7	26	4	17	42.1	21.3	5	6.0	1070	CI	BALKANS NW MACEDONIA SKOPJE
1903	5	28	3	58	40.9	42.7	-	5.8	1000	CI	TURKEY VARGINIS,CARDAHLI,MEHKEREK
1906	1	31	15	35	1	-81.5	25	8.8	1000	PB	ECUADOR OFF COAST
1907	1	14	21	36	18.2	-76.7	-	6.5	1000	PB	JAMAICA KINGSTON
1930	3	31	0	0	12.1	-86.2	-	-	1000	CI	NICARAGUA MANAGUA
1940	11	10	1	39	45.8	26.8	150	7.3	1000	CI	ROMANIA
1942	12	20	14	3	40.9	36.5	-	7.2	1000	CI	TURKEY NIKSAR, ERBAA
1960	5	22	19	11	-39.5	-74.5	33	9.5	1000	PB	CHILE PUERTO MONTT, VALDIVIA
1971	5	22	16	43	38.8	40.5	3	6.9	1000	CI	TURKEY BINGOL
1987	3	6	4	10	0.151	-77.821	10	7.2	1000	CI	ECUADOR NAPO PROVINCE, QUITO, TULCAN
1992	12	12	5	29	-8.48	121.896	28	7.8	1000	CI	INDONESIA FLORES REGION, MAUMERE, BABI
2002	3	25	14	56	36.062	69.315	8	6.1	1000	CI	AFGHANISTAN HINDU KUSH BAGHLAN, NAHR
1976	5	6	20	0	46.356	13.275	9	6.5	978	CI	ITALY NE, BALKANS NW SLOVENIA NW
1953	2	12	8	15	35.4	55.1	-	-	970	CI	IRAN TORUD
1913	12	21	15	37	24.15	102.45	10	7.2	942	CI	CHINA YUNNAN PROVINCE
1999	11	12	16	57	40.758	31.161	10	7.2	894	CI	TURKEY BOLU-DUZCE-KAYNASLI, ADAPAZARI,
1991	1	31	23	3	35.993	70.423	142	6.9	845	CI	AFGHANISTAN BADAKHSTAN, BAGHLAN, LAGHM
2001	1	13	17	33	13.049	-88.66	60	7.7	844	PB	EL SALVADOR
1946	5	31	3	12	39.3	41.2	-	5.9	840	CI	TURKEY USTUKRAN
1946	11	10	17	42	-8.5	-77.5	12	6.8	800	CI	PERU JOCAIBAMBA,CERRO ANGASCHAJ,CERRO S
1948	5	25	7	11	29.5	100.5	18	7.2	800	CI	CHINA SICHUAN PROVINCE
1988	11	6	13	3	22.789	99.611	18	7.0	738	CI	CHINA YUNNAN PROVINCE
1941	2	16	16	38	33.5	58.6	-	-	730	CI	IRAN MOHAMMADABAD
1924	12	2	0	0	-7.3	109.9	-	-	727	PB	INDONESIA JAVA WONOSOBO
1906	4	18	13	12	37.67	-122.48	20	7.9	700	PB	CALIFORNIA SAN FRANCISCO
1910	5	4	23	50	10	-84	-	6.0^a	700	PB	COSTA RICA CARTAGO, SAN JOSE
1911	4	18	18	14	31.23	57.03	50	6.7	700	CI	IRAN RAVAR
1968	9	1	7	27	34	58.2	15	6.3	700	CI	IRAN FERDOW
1935	4	11	23	15	36.3	53.5	14	6.8	690	CI	IRAN KEVSUT, ALBORZ, SARI

Year	Month	Day	Hour	Minute	Latitude	Longitude	Depth (km)	M_w	Deaths		Location
1976	8	16	16	11	6.262	124.023	33	8.1	690	PB	PHILIPPINES MINDANAO S
1920	1	3	21	48	19.26	-96.97	-	-	648	CI	MEXICO VERACRUZ COZAUTLAN, PUEBLA PA
2004	2	24	2	27	35.142	-3.997	-	6.4	628	CI	MOROCCO AL HOCEIMA, IMZOURENE, BENI AB
2005	2	22	2	25	30.754	56.816	14	6.4	612	CI	IRAN KERMAN PROVINCE ZARAND
1920	11	26	7	51	40.2	20	25	-	600	CI	ALBANIA TEPELENE, DRAGOTI, PESHTANI, M
1973	8	28	9	50	18.27	-96.6	84	7.3	600	CI	MEXICO VERACRUZ, MEXICO CITY
1979	12	12	7	59	1.598	-79.358	33	8.1	600	PB	COLOMBIA OFF SHORE, PACIFIC OCEAN
1977	12	19	23	34	30.95	56.47	31	5.9	584	CI	IRAN BAB-TANGOL
1976	7	14	7	13	-8.17	114.89	40	6.5	563	PB	INDONESIA BALI
1905	9	8	1	43	39	16	-	6.8	557	CI	ITALY MONTELEONE,TROPEA,NONTE PORO
1943	12	5	0	0	40	40	-	-	550	CI	TURKEY ANATOLIA NE
1992	10	12	13	9	29.778	31.144	22	5.8	545	CI	EGYPT CAIRO
1935	5	1	10	24	39.3	40.6	-	-	540	CI	TURKEY KIGI
2007	8	15	23	40	-13.386	-76.603	39	8.0	514	PB	PERU ICA, PISCO, LIMA
1922	11	11	4	32	-28.5	-70	25	8.5	500	PB	CHILE ATACAMA
1925	12	14	0	0	34.6	58.1	-	-	500	CI	IRAN BAJESTAN
1930	5	5	13	45	17.3	96.5	-	7.2	500	CI	MYANMAR (BURMA) PEGU, RANGOON
1947	9	23	12	28	33.4	58.7	-	6.8	500	CI	IRAN DUSTABAD
1957	5	26	6	33	40.7	30.9	-	7.2	500	CI	TURKEY ABANT

Table A.1: Earthquakes since 1900 that caused more than 500 deaths, from the NOAA Significant Earthquake Database (http://www.ngdc.noaa.gov/hazard/earthqk.shtml). Earthquakes that took place on a subduction plate boundary are marked “PB”; those that took place on faults that are not plate boundaries (see text) are marked “CI”. Only earthquakes resulting in 1000 deaths or more are plotted in Figure 2.

[a] Magnitude from Ambraseys, N. N. *Geophys. J. Int.* **121**, 545–556, 1995;

[b] Magnitude from [13].

Table A.2: Significant earthquakes, with estimates of the cost of the damage they caused (see Figure 1). Costs are taken from http://www.ngdc.noaa.gov/hazard/earthqk.shtml, and adjusted to 2011 US dollars using an annual inflation rate of 3.2%, which represents an average for the 20th century, from a number of sources including the US consumer price index calculation http://www.bls.gov/data/inflation_calculator.htm.

2011	3	11	142.369	38.322	9.0	27581	310000	310	[a]Honshu
1995	1	16	34.583	135.02	6.9	5502	217671	218	Kobe
2011	0	0	0	0	7.8	1500	200000	200	[b]Los Angeles Future
2008	5	12	31.002	103.322	7.9	87652	132992	133	Wenchuan
1999	8	17	40.748	29.864	7.6	17118	29187	29	Izmit
1994	1	17	0	0	6.7	33	28280	28	Northridge
1999	9	20	23.772	120.982	7.7	2297	22431	22	Taiwan
1976	7	27	39.57	117.98	7.5	242000	21081	21	Tangshan
2009	4	6	13.38	42.347	6.3	308	17500	18	L'Aquila
1990	6	20	36.957	49.409	7.4	40000	15501	16	Iran
1980	10	10	36.195	1.354	7.1	5000	13806	14	ElAsnam
2004	12	26	3.295	95.982	9.1	175827	12467	12	Sumatra
2011	2	11	172.701	-43.583	6.3	181	12000	12	Christchurch
1985	9	19	18.19	-102.53	8.0	9500	9073	9.1	Mexico
1906	4	18	37.67	-122.48	7.9	2000	9000	9.0	San Fancisco 1906
2010	1	12	18.457	-72.533	7.0	222570	8800	8.8	Haiti
2003	5	21	36.964	3.634	6.8	2266	6433	6.4	Algeria
2005	10	8	73.588	34.539	7.6	86000	6000	6.0	Kashmir
1999	0	0	23.6	38.11	6.0	143	4400	4.4	Athens
2001	1	26	23.419	70.232	7.7	19000	3594	3.6	Bhuj
1908	12	28	38.183	15.683	7.1	82000	2575	2.6	Messina
1915	1	13	42	13.5	6.9	29978	1234	1.2	Italy
1993	9	29	18.066	76.451	6.2	11000	560	0.6	Latur
1920	12	16	36.7	104.9	7.8	200000	439	0.4	Gansu
2003	12	26	28.995	58.311	6.6	31000	420	0.4	Bam
1939	12	26	39.8	39.5	7.7	32700	200	0.2	Erzincan
1978	9	16	33.386	57.434	7.4	20000	141	0.1	Tabas

[a] Estimate from Forbes 11/April/2011.

[b] Estimated by the USGS Multi-Hazards Demonstration Project [15].

Appendix B

The following list includes foreign participants at the Workshop, and speakers from within the UK. Stars indicate people who accepted and, though unable to attend the Workshop, contributed advice or material used in this report. The Workshop consisted of a day of lectures, and a second day of group discussions; these discussions were minuted and form the basis for this report.

- Roger Bilham, University of Colorado, Professor of Geological Sciences.
- Eric Calais, Professor of Geophysics, Purdue University.
  Science Advisor, United Nations Disaster Risk Reduction program, Haïti.
- Andrew Coburn, Risk Management Solutions, London.
  Vice-President, Emerging Risk Solutions.
- Nicola D'Agostino, Istituto Nazionale Geofisica Vulcanologia, Italy.
  Senior Researcher, National Earthquake Centre.
- *Mustafa Erdik, Director, Kandilli Observatory and Earthquake Research Institute, Istanbul.
- Manouchehr Ghorashi, Geological Survey of Iran, Tehran.
  Director, Research Institute for Earth Sciences.
- R. N. Iyengar, Jain University, Bangalore, India.
  Director, Centre for Disaster Mitigation.
- James Jackson, Department of Earth Sciences, University of Cambridge.
  Professor of Active Tectonics and Head of Department.
- Thorne Lay, Professor of Earth and Planetary Sciences, UC Santa Cruz.
  Director, Center for the Study of Imaging and Dynamics of the Earth.
- Sarosh Lodi, NED University of Engineering and Technology, Karachi.
  Dean, Civil Engineering and Architecture.
- Hamid Nazari, Research Institute for Earth Sciences, Geological Survey of Iran, Tehran.
  Head, Geology and Paleoseismology Department.
- Demitris Paradissis, National Technical University, Athens.
  Professor of Surveying Engineering and Director of the Dionysos Satellite Observatory.
- John Rees, NERC. Theme Leader.
- Giulio Selvaggi, Istituto Nazionale Geofisica Vulcanologia, Italy.
  Director, National Earthquake Centre.
- Robin Spence, Department of Architecture, Cambridge University.
  Emeritus Professor of Architectural Engineering, and Director of Cambridge Architectural Research Ltd.
- Costas Synolakis, University of Southern California.
  Professor of Civil and Environmental Engineering, and Director, Tsunami Research Center.
- Morteza Talebian, Research Institute for Earth Sciences, Geological Survey of Iran, Tehran.
  Head, Seismotectonics and Seismology Department.
- Brian Tucker, President, Geohazards International.
- John Young, Deputy Director, Overseas Development Institute.
- *Peizhen Zhang, China Earthquake Administration Director, Institute of Geology.