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Human casualties in earthquakes: modelling and mitigation

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ABSTRACT: Earthquake risk modelling is needed for the planning of post-event emergency operations, for the development of insurance schemes, for the planning of mitigation measures in the existing building stock, and for the development of appropriate building regulations; in all of these applications estimates of casualty numbers are essential. But there are many questions about casualty estimation which are still poorly understood. These questions relate to the causes and nature of the injuries and deaths, and the extent to which they can be quantified. This paper looks at the evidence on these questions from recent studies. It then reviews casualty estimation models available, and finally compares the performance of some casualty models in making rapid post-event casualty estimates in recent earthquakes.

1 INTRODUCTION

Earthquake impact and risk modelling is growing in importance. It is essential for the planning of post-event emergency operations; it contributes to the development of insurance schemes and to the planning of mitigation measures in the existing building stock, as well as the development of appropriate building regulations and controls for urban development. One of the most important earthquake impacts, and the one which is most widely quoted as a measure of an earthquake's severity, is the number of people killed and injured. To make progress in the reliability of earthquake impact modelling, it is therefore essential to be able to estimate the number of deaths and the number and types of injuries which may result from a given earthquake event.

However, making such estimates requires a more detailed understanding of the causative factors of earthquake deaths and injuries than is, in most cases, currently available. Given the infrequency in any location of lethal earthquakes (in the last decade there have been no more than 23 events causing 100 or more deaths worldwide), there are many basic questions for which evidence is at present very scarce. How are injuries caused? To what extent are numbers of injuries and deaths the result of ground shaking patterns, construction methods and income levels, and how are they affected by time of day, speed of search and rescue and other factors? To what extent can expected numbers of deaths and injuries be quantified? And how does this understanding enable us to know how to intervene to reduce the likely casualty rates in future earthquakes?

Over the last 3 years a series of international workshops have been held to try to gather together the evidence on these and related questions. The first workshops in Kyoto (November 2007) and Cambridge (June, 2009), included researchers and practitioners from Japan, Europe, the United States and elsewhere. They brought together engineers, architects, health professionals and emergency managers. The results of numerous recent field, analytical, and laboratory studies were presented, and a book containing a selection of the key presentations has recently been published (Spence, So and Scawthorn, 2010). This paper will first attempt to summarise recent evidence on these questions, drawing on the studies presented in this book. It will then summarise and compare models that include the number of casualties which have been developed to provide rapid estimates of the severity of an earthquake's impacts, based on the seismological information about the event available in the first few minutes after it has occurred. The performance of these models in recent events will then be evaluated and future developments in rapid impact modeling will be discussed.

2 FACTORS AFFECTING CASUALTIES IN EARTHQUAKES

2.1 *General*

Human casualties in earthquakes are mostly the result of the failure of buildings caused by ground shaking, affecting both their occupants and in some cases those outside buildings. But some deaths result from the failure of infrastructure (roads, etc.). Failure of buildings and infrastructure may also be the result of landslides or other ground instability. Casualties can also be caused directly by collateral hazards – landslides, tsunamis, and fire following earthquake. Recent evidence has shown that while casualties related to ground shaking remain overall by far the most numerous, in particular events (e.g., South Asia, 2004 and Concepcion, Chile, 2010), tsunami-related deaths may predominate. As seen in Kashmir, Pakistan (2005) and Wenchuan, China (2008), deaths directly from landslides can add significantly to the total casualty numbers. Moreover, there is evidence that building collapse rates can often be enhanced by localised land instability (e.g., in Kashmir, 2005 and in Haiti, 2010). There have been virtually no deaths from fire following earthquakes in the last two decades, as most earthquakes have occurred in areas where non-combustible materials predominate and utilities distributing combustible fuels are better protected. However, there remains a potential for casualties from this cause, particularly in areas where timber-frame buildings are the main building type. In any estimate of the total expected casualties from a given earthquake, all of these possible causes of casualties need to be considered.

This paper is concerned, however, with casualties associated with building failure. The number of such casualties will clearly depend on the population actually exposed (i.e., occupying the buildings affected at the time of the event), the performance of the buildings (damage to both structure and non-structural elements) in the event, and the relationship between the number and type of casualties and the behaviour of the buildings. Evidence on each of these factors is summarised in the following sections.

2.2 *Factors affecting occupancy/exposure of population*

The average population expected to be exposed to an earthquake can be estimated by the use of national census data or by the use of global datasets such as LandScan (www.ornl.gov/sci/landscan), which is derived from a variety of sources (Dobson et al., 2003). In order to estimate casualties, the population in the area at the moment of the earthquake and the distribution of this population into buildings of different types must be estimated.

The time of day of the event can be expected to be an important factor affecting population exposure; at night and early morning, most of the population can be expected to be at home in residential buildings; whereas during the daytime, according to the time of day, part of the population may be at work, in schools, or travelling. Residential buildings may be more or less vulnerable to earthquake ground shaking than schools and workplaces. In addition to these daily population movements, seasonal, cultural and touristic population movements can often affect the population exposed at the time of the event. In the Italian Appenine mountains which are frequently affected by earthquakes (e.g., Umbria-Marche, 1997 and L'Aquila, 2009; Zuccaro, 2010), many of the houses are second homes, infrequently occupied; in other earthquake areas (such as the Algarve in Portugal or the Azores islands), the normally resident population may be doubled or more by a summer influx of tourists (Ferreira et al., 2010).

There is evidence from some recent earthquakes that lower than expected death tolls were related to daytime events (e.g., Pisco, Peru, 2007 and Yogyakarta, Indonesia, 2007; So, 2009). However, different analyses of the pattern of earthquake deaths with time of day over a number of decades leads to the conclusion that time of day is a relatively small factor influencing earthquake death rates compared with other sources of uncertainty (Allen et al., 2009, Scawthorn, 2010).

A further factor which may influence the population exposed at the time of the event is a short-term warning of strong ground shaking. This may (rarely) be because precursory phenomena have given rise to a warning; more commonly when the pattern of earthquake ground motion contains a few seconds of low-level ground shaking before the most damaging shocks occur, sufficient to enable people to escape from vulnerable buildings to safer open ground. Evidence from Pisco, Peru (So, 2009) suggests that this may have influenced the unexpectedly low death toll in that earthquake.

2.3 *Factors affecting building damage*

When buildings suffer damage in earthquakes, their occupants are likely to be injured and even killed as a result. The relationship between occupant injury and building damage is complex, but the general rule prevails that the greater the damage to buildings, the greater the risk of casualties to occupants. Thus factors affecting vulnerability to building damage will also affect numbers of occupants killed or injured. Injuries to occupants may occur at levels of ground shaking which are insufficient to cause more than light damage to a building's permanent fabric, because the shaking may move furniture or filing cabinets, bring down light fittings, or cause cooking equipment to spill. There is much evidence of such injuries in studies of earthquake casualties from the 1999 Kocaeli earthquake (Petal, 2010), and the 2004 Niigata earthquake (Koyama et al., 2010). At a ground shaking level sufficient to cause damage to the fabric of the building, e.g., causing masonry walls, parapets and partitions to fail, injury levels are greater, and some deaths may occur, while complete collapse of a building is likely to cause virtually all occupants to be injured and a high proportion to be killed.

The expected damage level caused by a given ground shaking depends on the vulnerability of the building, which depends in turn on the form and quality of construction, age, degree of implementation of anti-seismic design and other factors. Globally, a very large number of separate building types have been recognised (Jaiswal and Wald, 2008), with collapse probabilities ranging from practically zero to 30% or more at a moderate level of ground shaking intensity (MMI=VII). Moreover, within any one vulnerability class the range of performance of individual buildings given the same general level of ground shaking is large; and the uncertainty in the proportion of buildings damaged at a given shaking level increases with level of damage. Very large uncertainties are associated to estimates of the proportion of completely collapsed buildings, those most lethal to their occupants (So and Spence, 2011).

Empirical studies of earthquake damage can be the basis of estimates of building vulnerability, and these usually record the proportion of a population of affected buildings at different levels of damage. Unfortunately, there has been no consistent agreement between survey teams about the definitions of the damage levels or what constitutes collapse or complete damage (Spence, 2010), which adds further uncertainty to the estimation of building damage for a given ground shaking intensity. Okada (1996) has proposed that the level of damage for correlation with numbers of killed and injured is best measured by the indoor space damage degree of a building after the ground shaking, i.e., the proportion of void space remaining in which it is possible that victims might survive, even if trapped.

2.4 *Factors affecting relationship between building damage and casualty levels*

A number of approaches to the estimation of casualties in earthquakes (e.g., NIBS and FEMA, 2008) have assumed a relatively fixed relationship between the numbers of casualties and the state of damage of a building, depending largely on the type of building, and its damage state. Recent studies however have shown that for some events, occupant behaviour at the time of the event can have a remarkable impact on the resulting casualties.

So (2009) showed that for those in single storey buildings in earthquakes in Indonesia and Peru, running outside when ground shaking begins appeared to reduce the number of occupants trapped and injured. However this option is not available for those in multi-storey buildings (Georgescu, 1988), if the earthquake occurs when its occupants are asleep, or for the elderly, and Petal (2010) found that exiting a building may in many cases be more dangerous than staying put. Koyama et al. (2010), in questionnaire studies following the Niigata earthquake showed that casualty rates (and types of injuries) depended not only on age and gender, but also the location of the occupants at the time of the event, and their subsequent behaviour. Petal (2010) showed that in the Kocaeli earthquake, comparatively few deaths occurred in 1-3 storey buildings by comparison with multi-storey apartment blocks.

The experience of those trapped immediately after the earthquake is commonly agreed to have an important influence on the numbers eventually killed. Search and rescue effectiveness and speed of response to rescue trapped survivors are agreed to be vital (Petal, 2010). In many events this comes mostly from the local population. The availability of medical care for the injured also affects survival rates as shown in the Pakistan earthquake (So, 2009).

All this indicates that the relationship between building damage and casualty levels is a complex combination of factors including the shape and form of construction of the building, occupant behaviour, and the availability of rescue and medical services, as well as the level and pattern of ground shaking, and cannot easily be reduced to simple lethality ratios. Moreover the available data on these factors is limited to a small number of events and is to some extent contradictory. The estimations of casualty models, as a result, are bound to have a high degree of uncertainty.

3 APPROACHES TO RAPID POST-EARTHQUAKE CASUALTY ASSESSMENT

3.1 *General approach*

Different approaches to the estimation of casualties are possible, depending on different types and levels of data input. Although in the past some approaches have claimed to able to estimate casualties based only on source parameters of the event (Samardjieva and Badal, 2002 and Nichols and Beavers, 2003), these have not proved reliable. Currently operational approaches depend on an estimate of the distribution of ground shaking, in intensity (EMS or MMI) units, such as the USGS ShakeMap, which derives from the source parameters of the event, a chosen ground motion prediction equation, a transformation of ground motion into shaking intensity parameters, and a correction for local site conditions (Jaiswal et al., 2010). All methods make use of some population distribution data by grid cells either using the Landscan 2007 gridded global population database, or other discrete data such as settlement populations.

Based on estimated distributed ground motion, the estimate of casualties typically follows one of three alternative procedures, described by Jaiswal et al. (2010) as *empirical*, *semi-empirical*, or *analytical* models.

An *empirical* model uses fatality data from past earthquakes to estimate a fatality rate based directly on the level of ground shaking; a *semi-empirical* model uses the local estimate of ground shaking to estimate the collapse rate (and perhaps heavy damage) rate for each of a number of different building classes based on empirical damage data, distributes the population among the different building classes according to the time of day of the event, and estimates a fatality (and perhaps injury) rate for each building class, given collapse or heavy damage; an *analytical* model is essentially the same as a semi-empirical model, except that collapse rates are based on an analytical procedure, such as HAZUS (NIBS and FEMA, 2008).

Thus a semi-empirical model needs to use information, for each location affected by the earthquake, on:

1. How the population in an affected location is divided among the buildings of different types,
2. The occupancy rate at the time of the event (i.e., the proportion of the normally resident population who are actually inside the building at that moment),
3. The ground shaking intensity level at that location,
4. The collapse and heavy damage rates for each of the different building classes at the ground shaking level, and
5. The casualty rates in each building class, given either heavy damage or collapse.

This information is generated in different ways in different approaches. The following paragraphs briefly summarise the bases of five separate approaches, the USGS PAGER Empirical and Semi-Empirical approaches, the WAPMERR QLARM approach, the Russian Academy of Sciences EXTREMUM approach, and the SISMA approach of the University of Naples PLINIVS Centre.

3.2 *WAPMERR QLARM*

The casualty estimation approach adopted by WAPMERR in their QLARM loss estimation method (Trendafiloski et al., 2010) is similar in concept to the semi-empirical approach of the PAGER group, also intended for worldwide earthquakes. A worldwide population and building stock exposure database has been incorporated into this model using a variety of data sources, though these are not publically available. The building stock and population for each city and rural area in the world is estimated, and divided between five vulnerability classes, A to E as defined in EMS-98 (Grünthal, 1998). In most countries, separate population distributions are used for different sized settlements (large:>20,000 inhabitants, medium: 2,000 to 20,000 inhabitants, and small or rural: <2,000 inhabitants). A variation in this population distribution to allow for diurnal population dynamics has been incorporated. A separate collapse rate for each vulnerabliity class is determined for each of 9 global regions using World Housing Encyclopedia (WHE) data (www.world-housing.net). For fatality and injury rates, data proposed by HAZUS (NIBS and FEMA, 2008), which depend on the assumed damage grade, are used as default values, and numbers of casualties at five separate casualty states are calculated. All model parameters have been calibrated and adjusted to obtain the best fit to data from historic earthquakes in the region.

3.3 *USGS PAGER empirical approach*

In the PAGER empirical approach (Jaiswal et al., 2010), a fatality rate is proposed as a proportion of the population exposed at each intensity level, and depends on the shaking intensity according to a lognormal function, with values of the two separate parameters defining the function, and an uncertainty factor, each for different countries or regions of the world. Population affected at any intensity is determined by overlaying the USGS ShakeMap (created within 30 minutes of the earthquake's occurrence) with the LandScan global population maps (www.ornl.gov/sci/landscan) and other population data sources.

Thus the fatality rate ν as a function of ground shaking intensity S is given by

$$\nu(S) = \Phi[\,(1/\beta)\ \ln\,(S/\theta)] \tag{1}$$

where β and θ are constants whose values for use in particular locations are derived from a regression on all fatal earthquakes in the given region. Values of these constants for particular regions are given in Jaiswal et al. (2010b).

3.4 *USGS PAGER semi-empirical approach*

The USGS PAGER semi-empirical approach aims to develop a better casualty estimate by using, for the area affected at each intensity level, the number of buildings and their vulnerability to collapse at the estimated ground shaking, combined with an estimate of the fatality (or lethality) rate as a proportion of total occupants, given collapse. To apply this approach for PAGER for worldwide earthquakes, the collapse rates were assembled using an expert-judgement approach with experts from 26 countries, contributing their input through the World Housing Encyclopedia (WHE).

The collapse fragility (CR) for each structure type was defined in terms of shaking intensity (S) as

$$CR\ (S) = A \times 10^{\,(B/(S-C))} \tag{2}$$

Where A, B and C are constants for the particular structure type derived either from specific structure collapse statistics or by regression on the expert judgement data assembled by the WHE-PAGER project (Porter et al., 2008). Values of the constants proposed are given in Jaiswal et al. (2010a).

In this model, generic fatality rates for collapsed buildings outside the US were derived from the results of the EU LessLoss project (So, 2007), while those for use in the US were taken from HAZUS (NIBS and FEMA, 2008).

3.5 *EXTREMUM*

The EXTREMUM system has been developed jointly by the Seismological Centre of the Russian Academy of Sciences and IGP Strasbourg, initially to estimate losses in Russia and the CIS (Commonwealth of Independent States) countries, but recently with worldwide application (Frolova et al., 2010). It uses Shebalin's 1968 ground motion prediction equations in terms of ground shaking intensity (MMSK-86 scale), with coefficients adapted for other territories from available data. The building stock in any area is divided into six different classes, and vulnerabilities derived from the European Macroseismic Scale 1992 (EMS-92) scale are used to assess physical damage. For the impact on the population, relationships between the ground shaking intensity and the rate of fatalities, missing and injured among the population of each class of building, derived from experienced losses in the CIS countries over the last 50 years, are used.

3.6 *PLINIVS model*

A similar approach has been developed by the Italian PLINIVS laboratory, based on extensive experience in Italy and applied to Italian earthquakes (Zuccaro et al., 2010). The model makes use of rapid post-event ground shaking estimates provided by INGV, and uses a model of the Italian building stock derived from national census data, dividing the building stock and population into five vulnerability classes as defined in European Macroseismic Scale (EMS-1998). The population was adjusted on the basis of extensive data on diurnal population dynamics, and seasonal populations dynamics was taken into account using a "touristic index". The damage distribution at each intensity was obtained from damage probability matrices (DPM) for each vulnerability class derived from surveys of damage in past earthquakes in Italy. The proportions of the occupants of any building expected to be injured or killed corresponding to each level of damage and for each vulnerability class are tabulated (Zuccaro et al., 2010). These are derived from survey data from past events in Italy.

3.7 *GDACS*

Potential disaster alerts are also regularly issued by GDACS, the Global Disaster Alert and Coordination System (www.gdacs.org), an entity supported by the United Nations and the European Commission. GDACS was established to issue alerts for disasters of all types, primarily for the benefit of the humanitarian aid community. GDACS earthquake alerts provide data on the earthquake source parameters, the population within radii from 1km to 200 km of the epicentre, the likelihood of tsunami, landslide or release of nuclear radiation, and give some indication of likely scale of the "humanitarian impact" (red, orange, green), but no direct estimates of casualties. These alerts are therefore not considered in the evaluation below.

4 EVALUATION AND COMPARISON OF MODELS IN RECENT EVENTS

This section attempts a comparison of the performance of some of the models described in the previous section in relation to recent major earthquake alerts. The events considered all took place in 2010, and were, chronologically: the 12 Jan Port-au-Prince, Haiti earthquake, the 27 Feb offshore Concepcion, Chile earthquake, the 13 April Qinghai, China earthquake, and the 3 Sept Darfield, New Zealand earthquake.

For each of these events WAPMERR provided a rapid alert using source parameters (magnitude, epicentre and depth) provided by others (USGS or GFZ Potsdam) and estimated maximum and minimum expected numbers of deaths and injured, using the QLARM system. The alert also provided a shakemap and a map showing settlements expected to have been affected, with mean damage levels.

Figure 1 shows an example, for the 2010 Chile event, of this latter type of map. The death and injury rates provided are subject to an expert review before being issued.

For each of these events the USGS provided a PAGER alert, giving the expected population exposed to different levels of ground shaking intensity but not casualty estimates. However the PAGER empirical method was used at the time of the event to estimate casualty numbers, and these estimates are now available in the PAGER archive (www.usgs.gov/pager). Since September 2010, PAGER's alerts have been reconfigured to include estimates of both fatalities, using the empirical approach as described above, and also estimated economic losses. The alerts are presented as alert ranges, intended for different levels of response and the median estimates are not published. The PAGER alert published for the Haiti earthquake is shown in Figure 2.

The PLINIVS model was applied to give a rapid estimate of the casualties following the L'Aquila earthquake in 2009, for the benefit of the Italian Department of Civil Protection. This was not widely circulated but the results have been published (Zuccaro et al., 2010); an estimate of 263 deaths 977 injured and 58,500 homeless was made within the first few hours after the earthquake, which compares well with the figures of 294 deaths or missing, 1,456 injured and 45,000 to 70,000 homeless reported by the Italian Department of Civil Protection one month after the event. Similarly estimates of casualties using the PAGER semi-empirical method and the EXTREMUM system are regularly made, but are not published, so they are not available for this evaluation.

The aspects of the alerts considered here are:

- The delay time between the occurrence of the earthquake and the issue of the alert
- The uncertainty range stated for casualties
- The accuracy of the estimate (was the actual number of people killed and injured within the predicted range).

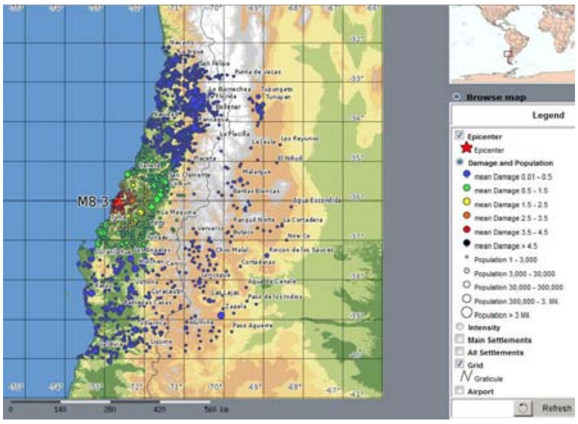

Figure 1. Chile Earthquake: WAPMERR map of estimated damage

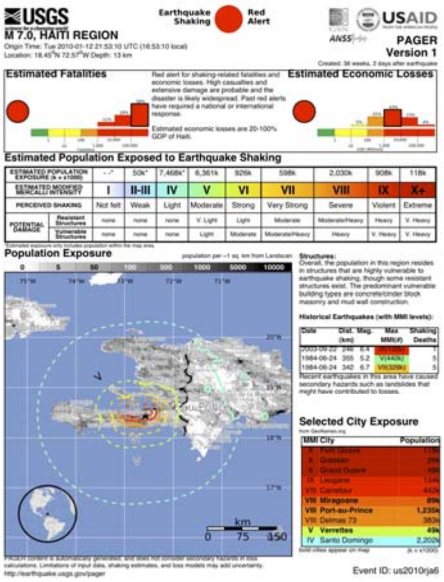

Figure 2. Haiti earthquake: USGS alert "one-pager" summary

4.1 *The M 7.0 12.1.2010 Haiti event, depth 13 km*

This earthquake occurred at 16:53 local time (21.53 UTC), and was immediately recognised from its magnitude, location and depth as a potential disaster. WAPMERR's alert, issued with a delay of 23 minutes after the event, stated that:

> "An earthquake with M7.0 to 7.2 has been reported 17 km from Port Au Prince, Haiti at a

> depth of only 10 to 20 km. This means there must be a disaster in Port Au Prince and neighbouring settlements. We estimate the number of fatalities between 2,000 and 10,000; the injured may range from 8,000 to 60,000. Maximum intensities are estimated as IX."

The PAGER alert, issued with a delay of 20 minutes after the event, also gave the depth as 10 km, and estimated populations of 981,000, 1,849,000 and 3,000 at MMI intensity levels of VIII, IX and X. PAGER also provided a Shake Map and added (in an automatically generated comment):

> "Overall, the population in this region resides in structures that are vulnerable to earthquake shaking, though some resistant structures exist."

Clearly a disaster was implied. The revised alert containing the casualty estimate corrected the depth and epicentral location, and the population exposed, and estimated a 58% probability of fatalities exceeding 100,000.

The full scale of the actual death toll became apparent only after a week or more, and eventually, according to official estimates, 316,000 people were reported to have been killed (reported by the Haitian government on the 1st anniversary of the earthquake, on 12th Jan 2011 New York Times, 13.01.2011) and about 300,000 were injured. Thus WAPMERR considerably underestimated the number of fatalities and injured. WAPMERR's Annual Report explains:

> "The building stock we had in our database was the same as that in neighbouring countries and that used by the World Housing Encyclopedia. It turned out the buildings in Haiti are about 10 times worse than in the neighbouring countries."

4.2 *The M8.8 offshore Chile earthquake of 27.2.2010, depth 35km*

This earthquake occurred at night, 2:34 local time (6:34 UTC), and its magnitude and location alone, an extremely large event close to a highly populated region, was sufficient to indicate its disaster potential. WAPMERR's alert was issued with a delay of 43 minutes after the event, using an estimated magnitude of 8.3 and depth of 18 km, with a range of expected fatalities between 300 and 4,000, and a range of expected injuries between 2,000 and 30,000. The initial PAGER alert, issued with a delay of 33 minutes, also gave the magnitude as 8.3 but gave a depth of 59 km. The PAGER alert gave populations of 2,468k, 10k and 0 in zones of MMI intensity VIII, IX and X. The automatically generated comment stated that:

> "Overall, the population in this region resides in structures that are vulnerable to earthquake shaking, though some resistant structures exist. Recent earthquakes in this area have caused tsunamis, landslides and liquefaction that may have contributed to losses."

PAGER's archived alert, with magnitude corrected to M8.8 and depth to 35km, gave an estimate of shaking related fatalities with a 38% probability between 100 and 1000, and a 42% probability of lying between 1,000 and 10,000; the median value was calculated as 1,179.

The final reported death toll for this earthquake was 521 dead and about 12,000 (http://earthquake.usgs.gov/earthquakes) injured. However, a substantial proportion, about 25% of this total death toll was due to the tsunami and not due to the ground shaking, which is the focus of calculation of the models.

Thus although the total casualty numbers of both models were within the expected range, both considerably overestimated the number of shaking deaths.

4.3 *The M6.9 Qinghai, China earthquake of 13.4.2010, depth 17km*

This earthquake occurred in the early morning at 07:49 local time (23:49 UTC) in a rural area of China without large population centres, but it triggered rapid alerts from both WAPMERR and USGS.

WAPMERR's alert, issued 23 minutes after the event, was a red alert; it used a magnitude of 6.9 and depth of 46.9 km, and estimated fatalities between 200 and 4,000, and injured between 500 and 10,000. It also noted that "the area is not densely settled but there are three sizeable cities within 50 km of the epicentre”.

The initial PAGER alert, issued 19 minutes after the event, gave a magnitude of 6.9 and a depth of 46 km, and estimated zero population in zones of MMI ≥ VIII, and a population of 13k in a zone of MMI VII. The automatic comment said, “overall the population in this region resides in structures that are highly vulnerable to earthquake shaking”. PAGER’s archived alert with the same magnitude, but with depth corrected to 17 km and some correction to the epicentral location, estimated a 56% probability of fatalities between 100 and 1000, and a 27% probability of fatalities between 1,000 and 10,000. The median fatality estimate was 445.

The final casualty figures reported by NEIC (http://earthquake.usgs.gov/earthquakes) were 2,698 people killed and 270 missing, and 12,135 injured. This is therefore an event in which the reported casualties were significantly higher than the median estimates of the models, but nevertheless within the published uncertainty bands in both cases. Perhaps the initially estimated depth of 46 km resulted in such an underestimate.

4.4 *The M7.0 Darfield New Zealand earthquake of 3.9.2010, depth 5 km*

The earthquake occurred at night, 4:35 local time (16:35 UTC), and occurred within 20 km of New Zealand’s second largest city of Christchurch. The expectation of large economic losses, if not casualties, triggered rapid alerts from WAPMERR and USGS.

The WAPMERR alert, issued 32 minutes after the event, used a magnitude of 7.2 and a depth of 16.1 km, and was green as far as expected casualties were concerned. Its estimate of fatalities was between 0 and 100, and of the injured, between 30 and 300. Its alert noted strong differences between different agencies in the estimated shaking in the epicentral location, which had a significant effect on the estimated population at different levels of intensity.

PAGER’s initial alert, created 29 minutes after the event, also gave the magnitude as 7.2 and depth as 16km. Populations of 202,000, 187,000 and 22,000 were estimated to have been exposed to intensity levels of VIII, IX and X. The alert noted that “overall, the population in this region resides in structures that are vulnerable to earthquake shaking, though some resistant structures exist”. From this initial assessment, considerable numbers of casualties would have been expected. The archived PAGER assessment, however, reduced the estimated depth to 5 km, but noted (correctly) that “overall the population in this region resides in structures that are highly resistant to earthquakes”, and assessed with 100% probability that there would be zero fatalities, although economic losses would be considerable.

Final reports are that there was no loss of life, and that there were only 2 serious injuries (http://earthquake.usgs.gov/earthquakes). Thus, as it turned out, the death toll was within the range of estimates from both models, although the injuries were fewer than the minimum value estimated by WAPMERR. Many observers have noted though, that had the event taken place in the evening or daytime, significant casualties in the badly damaged masonry-constructed part of the Central Business District would have been inevitable.

5 DISCUSSION

This review has highlighted the very large uncertainties that apply to even the best casualty estimation models if they are to be produced with delay times around 30 minutes after the event. At this stage, for many locations, the earthquake source parameters are still very uncertain, and errors in location and depth, as well as magnitude, can all have a very significant effect on estimated casualties. Wyss et al. (2011) have shown that for several events of the recent past, the very early errors in location can be of the order of 10 to 20 km, an error large enough to change by several orders of magnitude the casualty estimates in a region of concentrated urban population. Improvements in rapid reporting of the earthquake source parameters are needed to improve the early estimates of losses.

Lack of knowledge of the likely performance of the local structures is acknowledged to be another potential source of serious error. The available loss models are at present based on a very crude global building stock model, in which the expected performance of structures is assumed similar to that in nearby regions for which better data exists. However, there can be considerable local variations as proved to be the case in Haiti where the buildings were worse, and in Chile where they were better than anticipated. In the Haiti case, the size of the death toll may also have been increased by the concentration of population in the Port-au-Prince area, in excess of what the global population models used would have predicted. Another potential source of error is the exclusion from both models of tsunami and landslide deaths; in the Chile case, tsunamis were a significant cause of death.

Table 1. Comparison of model estimates with reported deaths and injuries in 2010 major events

	Measure	**Haiti**	**Chile**	**Qinghai**	**New Zealand**
WAPMERR	Delay (minutes)	23	43	23	32
	Deaths- min/max	2,000 to 10,000	300 to 4,000	200 to 4,000	0 to 100
	Deaths - median	4,500	1,100	894	NA
	Deaths range	5	13	20	NA
	Injuries min/max	8,000 to 60,000	2,000 to 30,000	500 to 10,000	30 to 300
	Injuries-median	22,000	7,700	2,200	95
	Injuries - range	7.5	15	20	10
PAGER	Delay (minutes)	20	33	19	29
	Deaths- min/max	2,700 to >500,000	40 to 127,000	40 to 5,300	0
	Deaths – median	165,000	1,179	445	
	Deaths range	3,500	2,800	135	0
Reported	Shaking deaths	316,000	399	2,698	0
	Injuries	300,000	12,000	12,135	2

In terms of the parameters chosen for comparison, delay time, uncertainty range and accuracy, the information obtained across the four events has been summarised in Table 1. All alerts were issued within about 30 minutes of the quake (the greatest being the 43 minutes for the Chile event). This can be considered a success and is a considerable achievement in terms of data management and processing. However, such a rapid response is likely to be at the expense of accuracy in the determination of earthquake source parameters, with considerable implications for the uncertainty in the resulting loss estimates.

Interestingly, the two models evaluated make very different claims for accuracy. The range of max and min given by WAPMERR in both fatalities and injuries span a range of between 5 and 15 (ratio of max to min). By contrast, the PAGER estimates reassessed as lognormal distributions indicate a ratio of max (interpreted as 5% exceedence probability) to min (95% exceedence probability) of around 3,000 (except for the New Zealand earthquake). With PAGER, the probability of the actual death toll falling outside the range is of course greatly reduced, but so is the utility of the estimate for purposes other than what it currently supports.

Since neither model publishes median estimates, comparison on this basis is somewhat unfair, but the inferred or estimated results are interesting and are shown in Table 1. For WAPMERR the central value is calculated as the geometric mean of max and min while for USGS the median value of the death toll has been taken directly from the background calculations. The numbers of fatalities were significantly underestimated by both models for the Haiti and Qinghai earthquakes, and the numbers of shaking fatalities significantly overestimated by both models for the Chile event. For injuries, WAPMERR similarly significantly underestimated in the same two cases (Haiti and Qinghai) but had an estimate for Chile that was about right.

However, it could be argued that the purpose of the alerts is simply to warn their recipients that a major humanitarian crisis is likely, and that rapid mobilisation is needed, rather than to be too precise about expected casualties. In this case both models provided the right conclusion in a timely manner, for each of the four events.

6 CONCLUSIONS

This study has shown that casualty models currently used for rapid post-event casualty estimation involve a high degree of uncertainty. This is in part due to uncertainty in the earthquake's source parameters at the early stage at which the alert results are needed. But it is also a reflection of poor understanding of much of the earth's building stock and its vulnerability characteristics, and of the human behaviour and response factors which influence survival rates in an earthquake.

Rapid post-earthquake casualty alerts are a very valuable way to develop casualty modelling, because they are testable, and can show how important the unknown factors are. Casualty models have a wider value: used as a component of loss modelling for scenario events or in a probabilistic sense they can be used as a tool in mitigation strategies – to develop targeted interventions in the building stock, to create viable insurance schemes, and to improve emergency preparedness, for example. Another recent application of casualty modelling, in the Southern California Shakeout exercise of 2008 (Shoaf and Seligson, 2010) had exactly this latter objective.

These models rely on studies of causes of casualties and human behaviour in earthquakes such as the survivor questionnaire studies of So (2010) and Koyama et al. (2010) and the event casualty studies of Alexander (2010), although these latter studies are far fewer and not yet systematically undertaken. Such studies would significantly add to the credibility of fatality rates used in loss estimation systems and must be encouraged.

The PAGER team are in the process of refining their methods: first, by exploring sub-regions in the empirical model to account for inherent vulnerability variations and secondly, by improving the estimates of lethality potential of buildings in the semi-empirical approach with available casualty data from recent events. Much of what needs to be done to improve loss modelling consists of improving our understanding of the world's building stock and its vulnerability – a large long-term project on which much work is currently in progress through global projects such as GEM (www.globalquakemodel.org), the World Housing Encyclopedia (with PAGER) and many national initiatives (Pomonis et al., 2010). Another promising direction of research is the investigation of the mechanics of injury in collapsing buildings, which may one day enable physics and anatomy-based models of casualty generation to be used (Ikuta and Miyano, 2010).

A start has been made with the work described in this paper, but much remains to be done to produce more reliable casualty models, and then to make use of what they can tell us to develop effective mitigation strategies for the reduction and eventual elimination of human casualties in earthquakes.

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