Integrating epidemiological and engineering approaches in the assessment of human casualties in earthquakes

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Abstract Earthquakes pose substantial risks of human health. Preparedness and mitigation strategies can reduce earthquake-related injuries and deaths and information from casualty models that predict earthquake outcomes can help communities prepare. This study identifies epidemiologic and medical risk factors for earthquake casualties, and compares them with engineering casualty models for the purpose of providing evidence that integrates these approaches. It aims to improve earthquake casualty modeling and to offer better accurate estimations. Epidemiological studies that used analytical designs and reported risk factors related to earthquake-induced casualties and studies that examined the association between medical preparedness and earthquake-induced casualties were reviewed. Engineering casualty estimation models were reviewed to identify which risk factors were considered in the models. Epidemiological studies identified the following risk factors: gender, age, socioeconomic status, physical disability and human behavior. Medical preparedness factors were also related to earthquake-induced injury and death. Global casualty estimation models do not currently consider these factors. This study provides evidence that integrating demographic and socioeconomic characteristics of the population and levels of medical preparedness into the existing casualty estimation models may improve their accuracy.

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1 Introduction

The estimated number of casualties is one of the central factors guiding emergency preparedness planning for a strong earthquake. The casualty burden from massive earthquakes is high. Earthquakes were the most deadly natural disaster in the last 24 years, resulting in over 800,000 deaths and 1.7 million injuries (46 % of the total death toll and 29 % of total injuries caused by natural disasters from 1990 to 2013) (EM-DAT 2014). Global trends toward urbanization combined with an increase in population density, poverty and social gaps increase the vulnerability of urban centers in the face of natural disasters, including earthquakes (Tekeli-Yesil 2006; Donner and Rodriguez 2008). Casualty modeling has traditionally been conducted using engineering methods, which focus only on damage to the built environment. Thus, the major source of information for community preparedness activities does not consider the exposed population and has rarely integrated human factors.

Several studies have examined the association of earthquake casualties with various seismic factors such as the magnitude of the earthquake (Alexander 1985; Samadjieva and Badel 2002), ground motion parameters such as peak ground acceleration (Shoaf et al. 1998; Mahue-Giangreco et al. 2001), shaking intensity and distance from epicenter (Liang et al. 2001). These factors do not account for the wide variations in earthquake casualties.

Fig. 1 Fatal earthquakes (over 1000 fatalities) since the year 2000 (the figure is based on data from the USGS website)

For example, magnitude is not strongly associated with the number of casualties in each event.

Based on existing studies, damage to buildings is considered the most important factor causing injury and death in earthquake events worldwide (Jaiswal et al. 2009; Peek-Asa et al. 1998; Noji and Kelen 1990; Spence et al. 2003; Wald et al. 2011; Porter et al. 2008; Jaiswal et al. 2009). Countries such as Japan and New Zealand, which have implemented strict seismic building codes and invested resources to enhance community preparedness, have demonstrated a dramatic decrease in the number of earthquake casualties compared to other developed countries such as China, India or Haiti, which still present high vulnerability to earthquakes (Paton et al. 2010; Crowley and Elliott 2012). This is demonstrated in Fig. 1, which presents 13 earthquakes that occurred from the year 2000 onwards. All these deadly events except one took place in developed countries with poor standards of building construction. However, the populations that occupy buildings have various characteristics in different countries and regions, which may play a crucial part in enhancing or impeding vulnerability to earthquakes, ultimately influencing the number of casualties in a given event. These nonstructural variables include individual characteristics, such as gender, age, physical disabilities and behavioral strategies; household characteristics, such as socioeconomic status (usually household income); and community characteristics, such as the existence of search and rescue teams and the medical aid response.

Evidence from other natural events such as floods suggests that communities with socially vulnerable populations experience more casualties (Cutter et al. 2003; Zahran et al. 2008). In light of recent events such as the 2010 Haiti earthquake, this finding should be investigated in the specific context of earthquake loss estimation and casualty modeling. This paper reviews the state of knowledge of epidemiological and engineering research regarding earthquake-induced casualty assessment and proposes a theoretical framework to combine these two approaches. The potential influence of demographic and socioeconomic parameters is presented and assessed in terms of the vulnerability of the population and the relevance of their integration into engineering-based casualty estimation models, to combine a holistic approach with casualty assessment from earthquakes.

2 Methods

Three parallel literature reviews were conducted to examine: (1) the role of human factors, (2) the role of medical preparedness regarding earthquake-induced casualties, and (3) earthquake loss estimation models. Studies were identified through four computer-based literature search engines: PubMed/MEDLINE, Web of Science, Scopus and Google scholar (the last one in order to collect ‘gray’ literature). For all three topics of review, the year of publication was limited from January 1985 to March 2014, and only publications in English were included.

2.1 Review of human factors and earthquake-induced injury and mortality

Key words used to extract relevant articles were earthquake*, casualties*, injury*, death* and risk factors*. A total of 1042 abstracts were identified. Articles were included in this review if they focused on risk factors that were related to the previously mentioned human factors (i.e., individual and household characteristics) and used analytical designs (such as cross-sectional or case-control studies) that presented a quantified measure of the different

risk factors (e.g., odds ratio or beta coefficient). Articles were excluded from this review if they had a descriptive design and did not present any measurable effect size (i.e., regression coefficient) or if it focused on casualties from other disastrous events rather than earthquakes or from earthquakes' secondary events (such as tsunami or landslides). These criteria used to screen all abstracts included. Thirteen studies met these criteria and were included in this section (Shoaf et al. 1998; Mahue-Giangreco et al. 2001; (Liang et al. 2001; Peek-Asa et al. 2003; Chou et al. 2004; Doocy et al. 2009, 2013; Ellidokuz et al. 2005; Dong et al. 2012; Kolbe et al. 2010; Osaki and Minowa 2001; Roces et al. 1992; Armenian et al. 1992). The steps of the literature review are described in Fig. 2. The covariates examined in each study and their effect estimates were identified.

2.2 Review of medical preparedness and earthquake-induced injury and mortality

Key words used to extract relevant articles were earthquake, casualties,* injury*, death*, rate*, risk factors*, preparedness* and medical care*. A total of 1050 abstracts were identified. Studies were eligible for inclusion if they specifically measured the association between receiving medical aid or preparedness of medical responders in hospital or pre-hospital settings and mortality or injury rates after an earthquake, and if they presented measurable results of this association (i.e., regression coefficient or difference in casualty rates). Studies were excluded from this section if they did not present any measurable results or if focused on casualties from other disastrous events rather than earthquakes or from earthquakes' secondary events (such as tsunami or landslides). These criteria used to screen all abstracts included. Eight studies met these criteria and were included in this section (Noji et al. 1993; Pretto et al. 1994; Tanaka et al. 1998; Fawcett and Oliveira 2000; Liang et al. 2001; Bissell et al. 2004; Jiang et al. 2012; Wen et al. 2012). Several additional

Fig. 2 Flow chart of the literature review ‘human factors and earthquake-induced injury and mortality’

studies were included in this section for the purpose of establishing a theoretical framework for the association between medical preparedness and response and the number of casualties in earthquake events (Schultz et al. 1996; Peek-Asa et al. 1998; Ashkenazi et al. 2005; Ramirez and Peek-Asa 2005; Macintyre et al. 2006; Bayard 2010; Bartal et al. 2011; Haojun et al. 2011; Archer et al. 2011). Although these studies did not quantitatively measure the association between medical preparedness and response and earthquake casualties, they contributed through establishing the need for evidence-based and theoretically driven modeling. Summaries of 14 articles with analytical designs ($n = 14$) that were included in the first two sections are presented in Table 1.

2.3 Review of earthquake casualty assessment methods and models

This section describes a state-of-the-art review of earthquake engineering-based casualty models currently in use around the world. Key words used to extract relevant data were earthquake*, seismic hazard*, casualty*, estimation*, assessment*, engineering*, model* and approach*. A total of 70 studies were identified, of which seven that represented the four common approaches in engineering-based casualty estimation (Maqsood and Schwarz 2011) were chosen (Samadjieva and Badel 2002; Porter et al. 2008; Jaiswal and Wald 2010a, b; Jaiswal et al. 2011; Spence and So 2009; FEMA 2003). Special emphasis was given to the HAZUS-MH loss estimation model since it is considered the ‘state of the art’ model in this field, currently used not only in the USA, but also around the world (Menezes and Inyang 2012).

3 Results

The majority of epidemiological studies were from regions with well-developed health infrastructures, such as the USA, Taiwan, Armenia, Turkey and Japan. Several recent studies focusing on the 2010 Haiti earthquake were found, but many regions with high earthquake incidence and casualties do not have published studies in the research literature (e.g., Pakistan, Sumatra).

3.1 Individual and household characteristics and earthquake-induced injury and death

Studies that examined the effects of gender had conflicting results, finding either no difference by gender or a higher rate of casualties among women. Studies from the USA, Taiwan, Turkey and Haiti found no differences in the risk of injury and death by gender (Mahue-Giangreco et al. 2001; Liang et al. 2001; Ellidokuz et al. 2005; Doocy et al. 2013). Among the four studies that found women at higher risk of injury and death, two from the USA (Shoaf et al. 1998; Peek-Asa et al. 2003) had the highest odds ratios (OR) for increased risk of injury of 1.64 (95 % CI N/A) and 2.4 (95 % CI 1.2, 5.1), respectively. Studies from Taiwan and Peru found women to be at higher risk of injury (Doocy et al. 2009) and death (Chou et al. 2004), but with smaller odds ratios: OR 1.2 (95 % CI 1.1, 1.3) and OR 1.6 (95 % CI 1.0, 2.7), respectively. The USA and Taiwan had conflicting findings, with studies in both regions reporting increased risk of females and no significant differences related to gender regarding the same earthquake events.

Table 1 Articles that used analytical methods ($n = 14$) to identify and quantify risk factors related to earthquake-induced injury and mortality

No.	Publication	Event(s)	Magnitude	Study design	Risk factors and related risk
1	Roces et al. (1992)	1990 Luzon, Philippines	7.7	Unmatched case-control study. Cases were individuals who sustained physical injuries during the earthquake, and controls were uninjured individuals who were in the same neighborhoods as cases during the earthquake	<i>Human behavior</i> —leaving a building during the earthquake was a protective behavior from sustaining injuries (compared to those who stayed inside buildings) (OR 0.3; 95 % CI 0.2, 0.8)
2	Armenian et al. (1992)	1988, Armenia	6.9	Case-control study. Cases were hospitalized with injuries from the city of Leninakan as a result of the earthquake. Controls had not been hospitalized and were selected from another household in the same neighborhood	<i>Human behavior</i> —Individuals who stayed indoors during the earthquake had 4.8 times greater risk of injury compared to those who ran outside (95 % CI 2.3, 10.0)
3	Noji et al. (1993)	1988, Armenia	6.9	Case-control study. Cases were hospitalized with injuries from the city of Leninakan as a result of the earthquake. Controls had not been hospitalized and were selected from another household in the same neighborhood	<i>Medical care</i> —case subjects (hospitalized) waited longer to be rescued and to receive medical care than did controls who were not hospitalized (OR 2.32; 95 % CI 1.0, 5.2)
4	Shoaf et al. (1998)	Whittier Narrows 1987; Loma Prieta 1989; Northridge 1994; all in California, USA	5.9, 7.1, 6.8	Cross-sectional design. Telephone survey to households in affected areas and analysis of demographic injury predictors	<i>Age</i> —older individuals were less likely to be injured, every 10-year increase in age decreased risk of injury (OR 0.7, 95 % CI N/A); <i>gender</i> —women had 1.64 times risk of injury compared to men (95 % CI N/A)
5	Mahue-Giangreco et al. (2001)	1994 Northridge, California	6.7	Cross-sectional design. Medical records were collected from hospitals who cared for the earthquake casualties	<i>Age</i> —individuals over the age of 60 had a higher risk of severe injuries compared to younger people (OR 2.69; 95 % CI 1.3, 5.4); <i>gender</i> —not significantly associated with risk of injury severity
6	Liang et al. (2001)	1999 Chi-Chi, Taiwan	7.3	Cross-sectional design. Crude casualty data were collected from government reports, local health bureaus and hospitals	<i>Age</i> —significantly related to earthquake mortality (coefficient = 0.101; 95 % CI = 0.076, 0.125); <i>gender</i> —not significantly associated with earthquake-related mortality; <i>medical beds/10,000 people</i> —was significantly related to earthquake mortality (coefficient = 0.012; 95 % CI = 0.003, 0.002); <i>physicians/10,000 people</i> —significantly related to earthquake mortality (coefficient = −0.153; 95 % CI = −0.201, −0.095)

Table 1 continued

No.	Publication	Event(s)	Magnitude	Study design	Risk factors and related risk
7	Osaki and Minowa (2001)	1995 Great Hanshin earthquake, Japan	7.2	A case-control study. Cases included all earthquake-related deaths in one affected city, and controls were randomly selected from survivors living in the same neighborhood as each case	<i>Physical disability</i> —a risk factor for earthquake-related death (OR 1.6; 95 % CI 1.0, 2.7). When the analysis was limited to people who lived in intact or partially destroyed dwellings, the risk increased (OR 5.6; 95 % CI 1.6, 19.8)
8	Peek-Asa et al. (2003)	1994 Northridge, California	6.7	Population-based case-control study. Cases included fatal and hospital admitted injuries, and controls were drawn from a population-based phone survey	<i>Age</i> —individuals over the age of 65 had 2.9 times the risk of injury as younger people (95 % CI 1.2, 7.4); <i>gender</i> —women had 2.4 times greater risk than men (95 % CI 1.2, 5.1)
9	Chou et al. (2004)	1999 Chi-Chi earthquake, Taiwan	7.3	A population-based cohort study. Data were collected regarding 84 % of the population in the affected area, through the family registration database (Ministry of Interior) and the National Health Insurance Program	<i>Age</i> —significantly associated with earthquake-related death. The risk increased with age, e.g., adults above the age of 55 had 3.5 (95 % CI 2.8, 4.5) times greater risk of dying in the earthquake and adults above the age of 65 had 5.5 (95 % CI 4.4, 6.8) times greater risk; <i>gender</i> —women had 1.2 greater risk of dying in the earthquake compared to men (95 % CI 1.1, 1.3); <i>physical disability</i> —individuals with moderate disability had 1.7 times higher risk of earthquake-related death (95 % CI 1.2, 2.3); <i>socioeconomic status</i> —the degree of vulnerability to the earthquake-related death increased with decreasing monthly wage (OR 2.2; 95 % CI 1.6, 3.0)
10	Ellidokuz et al. (2005)	2002 Ayfon, Turkey	6.1	Cross-sectional study; 90.5 % of the population of the city of Eber, that was particularly affected by the earthquake, were interviewed based on a questionnaire	The risk of earthquake-induced injury and death was higher among women, the elderly and children, but this was not statistically significant
11	Doocy et al. (2009)	2007 Ica, Peru	8	A population-based cluster survey of households in the region most affected by the earthquake	<i>Age</i> —the risk of injury increased by 3 % (95 % CI 2–4 %) per additional year of age; <i>gender</i> —the risk of injury was 1.6 times greater among adult females (95 % CI 1.0, 2.7); <i>socioeconomic status</i> —members of households of lower economic status faced increased risk of injury. Risk of injury decreased by 3 % with increase in pre-earthquake monthly household income

Table 1 continued

No.	Publication	Event(s)	Magnitude	Study design	Risk factors and related risk
12	Kolbe et al. (2010)	2010 Haiti	7	Retrospective design; pre-earthquake study in the Port-au-Prince metropolitan in 2009. After the quake, another survey was conducted interviewing 93 % of the households participated in original survey	<i>Age</i> —youth under 18 were 5.8 times more likely to have been killed during the earthquake than adults (95 % CI 4.0, 8.3)
13	Dong et al. (2012)	2012 Sichuan	8	Retrospective design; medical files of 1491 patients injured in the quake were reviewed	<i>Age</i> —casualties older than 64 years were at higher risk of mortality ($B = 1.59$, $CI = N/A$)
14	Doocy et al. (2013)	2010 Haiti	7	A cross-sectional cluster survey; 1200 households in Port-au-Prince affected by the earthquake were surveyed	<i>Age</i> —adults aged 50 + had increased mortality risk (OR 2.8, 95 % CI 1.6, 4.7); <i>gender</i> —not significantly associated with risk of earthquake mortality

Studies that examined age had inconsistencies, but reported some common results. Those spanning 25 years and a variety of geographic regions found higher rates of casualties among the elderly and children. One exception was a study from the USA that reported decreased risk of earthquake-induced injury with increasing age (OR 0.7, 95 % CI N/A) (Shoaf et al. 1998). Among the seven studies that found the elderly to be at higher risk for injury and death, Chou et al. from Taiwan (2004) had the highest odds ratio for increased risk of death of 5.5 (95 % CI 4.4, 6.8). Three studies from the USA and Haiti (Mahue-Giangreco et al. 2001; Peek-Asa et al. 2003; Doocy et al. 2013) found lower odds ratios of increased risk of injury OR 2.69 (95 % CI 1.34, 5.4), OR 2.9 (95 % CI 1.2, 7.4) and increased risk of death OR 2.8 (95 % CI 1.66, 4.72), respectively. Two other studies from Taiwan and China (Liang et al. 2001; Dong et al. 2012) also found age to be significantly associated with higher mortality and reported coefficient value of 0.101 (95 % CI 0.076, 0.125) and B coefficient of 1.539 (95 % CI N/A). A study from Peru (Doocy et al. 2009) did not report odds ratio or coefficient values, but stated that increases in age increased the risk of injury by 3 % (95 % CI 2, 4).

Studies from the USA reported conflicting findings, with studies regarding the same event reporting that the elderly were at higher risk of injury and death and that increased age lowered risk. Studies from Haiti (Kolbe et al. 2010) and Taiwan (Chou et al. 2004) found children to be at higher risk of death, and both reported similar odds ratios of 5.8 (95 % CI 4, 8.3) and 5.5 (95 % CI 4.4, 6.8), respectively.

Although many articles discussed the role of poverty and socioeconomic status on earthquake casualties, few measured the risks related to these factors (Cannon 1994; Fothergill and Peek 2004; Kahn 2005). Figure 1 demonstrates that most deadly earthquakes occur in developing countries rather than in developed countries, but even when an earthquake strikes a well-developed country such as the USA, there is evidence that low-income households were more affected than high-income households (Fothergill and Peek 2004). However, studies from Taiwan (Chou et al. 2004) and Peru (Doocy et al. 2009) used analytical methods to measure the role of socioeconomic status as a risk factor for earthquake-related injury and death. The Taiwanese study found that the degree of vulnerability to earthquake-related death increased with decreasing monthly wage (OR 2.2, 95 % CI 1.6, 3.0). Similarly, the study from Peru found that members of households with lower economic status faced increased risk of injury and that the risk decreased by 3 % per additional 100 soles (Peruvian currency) of monthly household income (Doocy et al. 2009).

Only two studies directly assessed the link between physical disability and the risk of earthquake-induced death; both found a higher rate of casualties among physically disabled individuals. The Japanese study (Osaki and Minowa 2001) found an odds ratio of 1.9 (95 % CI 1.0, 3.4), and similarly, the study from Taiwan (Chou et al. 2004) found an odds ratio of 1.7 (95 % CI 1.2, 2.3).

Two studies examined the effect of human behavior during an earthquake on the risk of injury and death and found that exiting the building decreased the risk of injury and death. The first study, from the Philippines (Roces et al. 1992), found a lower odds ratio for injury (OR 0.3; 95 % CI 0.1, 0.9) among subjects who were outside buildings. Similarly, a study from Armenia (Armenian et al. 1992) found a higher odds ratio for injury (OR 4.8; 95 % CI 2.34, 10.0) among subjects who remained inside.

Ethnicity was discussed in American studies and was found a significant risk factor affecting injury and death in earthquakes (Shoaf et al. 1998; Mahue-Giangreco et al. 2001), although not consistently. Since ethnic groups and their characteristics vary from region to region, this issue is not addressed here.

3.2 Medical preparedness and earthquake-induced injury and mortality

A large earthquake is likely to incur mass casualties. This has several implications for the local health system in both pre-hospital and hospital settings and on the aftermath of the event. Many studies have determined that rapid extrication of victims trapped under rubble significantly reduces mortality in earthquakes. The victims tend to have typical injuries (e.g., crush syndrome), which require knowledge of appropriate treatment methods (Schultz et al. 1996; Peek-Asa et al. 1998; Ashkenzai et al. 2005; Ramirez and Peek-Asa 2005; Macintyre et al. 2006; Bartal et al. 2011). Therefore, the existence and efficacy of search and rescue teams combined with access to pre-hospital care may have a crucial effect on the number casualties (Haojun et al. 2011). Local hospitals, which are expected to provide care for the victims, may be overwhelmed by the large number of casualties arriving in a short period. In addition, providing medical aid in a disaster-affected area also entails working under extreme conditions, such as reduced workforce, limited medical supplies and resources compared to the increased demands for medical care (Archer et al. 2011; Jiang et al. 2012), and requires particular knowledge and preparedness for this scenario. Nonetheless, hospitals are considered the principal providers of immediate medical care after catastrophic events, and the general assumption is that a well-prepared hospital and medical staff could reduce mortality after a serious earthquake (Schultz et al. 1996; Pretto et al. 1994). Only one study directly assessed health sector preparedness levels and the association with earthquake-induced mortality. The findings revealed that ‘low prepared’ regions had five times more fatalities per 100 injuries compared to ‘medium prepared’ regions and that ‘high prepared’ regions had 30 times fewer fatalities compared to ‘medium prepared’ regions (Bissell et al. 2004). Other studies found that the mortality rate for severely injured victims was 15–25 % and was usually higher in frontline hospitals and that these rates may decline to 9–3 % or even lower, if proper medical care is not delayed (Pretto et al. 1994; Tanaka et al. 1998; Fawcett and Oliveira 2000; Jiang et al. 2012; Wen et al. 2012). Some studies reported findings that relate to this subject indirectly. An Armenian study found that subjects who were severely injured in an earthquake waited longer to receive medical care compared with subjects who with mild injuries (OR 2.32; 95 % CI 1.0, 5.2) (Noji et al. 1993). Another study from Taiwan reported that the number of available hospital beds (coefficient value 0.012; 95 % CI 0.003, 0.022) and the rate of doctors per 10,000 people (coefficient value −0.153; 95 % CI −0.210, −0.095) affected the risk of mortality among the population exposed to an earthquake (Liang et al. 2001). Furthermore, complications such as gangrene, sepsis and disabilities due to delayed medical care were reported after the 2010 Haiti earthquake (Bayard 2010).

3.3 Earthquake casualty assessment models

Four approaches are often used to estimate casualties in earthquakes (Maqsood and Schwarz 2011). The empirical approach consists of directly correlating the magnitude/intensity of the earthquake and the size of the population in the area at times of the earthquake, based on historic earthquake statistics (Samadjieva and Badel 2002; Jaiswal and Wald 2010a). The semiempirical approach builds on the empirical approach by additionally accounting for the types of buildings that characterize the area and damage rates according to the different structures (Jaiswal and Wald 2010b). The purely analytic approach predicts behavior of buildings and their effects on individuals inside them, based on seismic hazard analysis (Porter et al. 2008; Spence and So 2009). An expansion of the other approaches that include all the aforementioned parameters and consider the population distribution in various occupancies and time frames, e.g., day, night and commute time, has been proposed (FEMA 2003).

In regions that have experienced numerous earthquakes with high numbers of fatalities, typically developing countries with dense populations living in vulnerable structures, enough data exist to calibrate fatalities from the historical earthquake record alone (FEMA 2008). In such regions, building inventories are typically lacking, as are systematic analyses of their vulnerabilities; hence, analytical tools are inadequate for loss estimation. In contrast, in the most highly developed countries, particularly those with substantive building codes, structural responses are more easily analyzed and information on their distribution and occupancy is more readily available (Li et al. 2011; Jaiswal and Wald 2010a). Due to the success of such building codes, for the purpose of fatality loss modeling, this category of countries typically has had relatively few fatal earthquakes, making it difficult to use empirical calibration from past events alone. In such cases, fatality estimates are largely informed from analytically derived collapse rates and inferred fatality ratios given a structural collapse (Jaiswal et al. 2011; Jaiswal and Wald 2010a, b). The last approach is applied in the HAZUS-MH loss estimation model (FEMA 2003), which is an American loss estimation methodology that can be utilized globally in different countries and regions. In HAZUS-MH, casualties are calculated as a function of building damage for given ground accelerations. Some demographic data such as age, ethnicity and household income are entered into the database, but these data are used only for estimating the expected displaced population and shelter needs and not to calculate casualties. Factors such as gender, disability and expected behavior during earthquakes are not taken into account in the current methodology. Medical preparedness and response is also a factor which is not considered at this time (FEMA 2003). Table 2 summarizes the information in

Table 2 Demographic and socioeconomic factors used by the HAZUS-MH social loss modules to estimate the rate of casualties and displaced population

	Casualty rate estimation	Displaced population estimation	Publications addressing this issue
Age	—	+	$N = 9$ Shoaf et al. (1998), Mahue-Giangreco et al. (2001), Liang et al. (2001), Peek-Asa et al. (2003), Chou et al. (2004), Doocy et al. (2009), Kolbe et al. (2010), Doocy et al. (2013), Dong et al. (2012)
Gender	—	—	$N = 8$ Shoaf et al. (1998), Mahue-Giangreco et al. (2001), Liang et al. (2001), Peek-Asa et al. (2003), Chou et al. (2004), Ellidokuz et al. (2005), Doocy et al. (2009), Doocy et al. (2013)
Ethnicity	—	+	$N = 2$ Shoaf et al. (1998), Mahue-Giangreco et al. (2001)
Physical Disability	—	—	$N = 2$ Osaki and Minowa (2001), Chou et al. (2004)
Household income	—	+	$N = 2$ Chou et al. (2004), Doocy et al. (2009)
Behavior during an earthquake	—	—	$N = 2$ Roces et al. (1992), Armenian et al. (1992)
Medical preparedness	—	—	$N = 1$ Bissell et al. (2004)

+ Indicates a factor which is accounted for in the module

— Indicates a factor which is not accounted for in the module

this section and emphasizes the gaps between the epidemiological and engineering approaches for earthquake-induced casualty estimations.

4 Discussion

Despite increasing efforts to prepare for and mitigate the effects of earthquakes, they cannot be predicted and continue to cause loss of human life, severe disability and property damage. Recent events in China (2008), Haiti (2010) and Japan (2011) have illustrated the difference between earthquakes that occur in developing countries compared to those in developed countries. When examining these events, the size of the earthquake (amount of energy released) and other microseismic characteristics have limited influence on casualties, indicating that other parameters related to the characteristics of the exposed population may play a key role in outcomes.

The concept of vulnerability in the natural hazard field embraces physical, social, economic and environmental dimensions (Smith 2013). Modern casualty estimation models are based mainly on the vulnerability of the built environment and its performance under different ground accelerations (FEMA 2003). However, a gap exists between factors described in the literature as increasing the risk of earthquake-induced injury and death and the factors considered in these models. The present study revealed that population characteristics, such as gender and age distribution, a physical disability, socioeconomic status, and human behavior during the event, affected the choice of protective strategy, all of which have a crucial influence on the number of casualties from a given event. These factors have been documented in descriptive reports after earthquakes throughout history and were significant in the analytical studies reviewed here. However, these factors have different effects in different earthquakes and could be important interaction variables with seismic and built-environment factors. Predictors are likely to be highly interactive and varied based on the parameters of the earthquake and its location. For example, increased risk of death among the elderly and those with disabilities could be tied both to the types of structures and to the types of behaviors—such as an inability to evacuate the building (Peek-Asa et al. 2003; Chou et al. 2004). However, these factors that represent human vulnerability to disasters are not currently integrated in casualty estimation models, a fact that can alter the outcomes of the risk assessment and management. The concept of human vulnerability to disasters refers to social and economic fragility, lack of social resilience and abilities to cope. Vulnerability (among other—human vulnerability) is considered a key factor determining the potential risk from a given hazard. Interacting with the amount of exposure to a hazard and the extant of capacity measures (e.g., medical preparedness and response), it affects the consequences of disastrous events worldwide (Birkmann, 2006). Therefore, human vulnerability assessment serves as a tool for effective risk assessment in terms of the expected number of casualties in a future event and also as a measure of disaster risk reduction achieved by empowering vulnerable populations (UNISDR 2014).

Furthermore, in most emergency plans, hospital and staff preparedness are assumed important in mitigating the number of casualties and injury severity (Barbera et al. 2009). Great efforts are invested to improve the level of preparedness among healthcare facilities and staff in order to obtain the appropriate response to future events, primarily manifested by increasing knowledge and improving the ability to provide adequate care as quickly as possible (Ben Natan et al. 2013). These efforts, as suggested from the studies reviewed in this work, may reduce the

mortality rates of critically injured individuals by tens of percent. This increases the need to evaluate the level of medical preparedness in different regions and to apply the findings when estimating casualties or planning disaster responses for future events. Another issue related to casualty rates and to the delay in providing medical aid is disruption to transportation infrastructure as a result of an earthquake, which may cause roadway-related injuries and hamper efforts to evacuate casualties to hospitals (Schultz, et al. 1996; Chan et al. 2006; Wang et al. 2009). This issue was not addressed in this current study, but needs to be investigated and considered further when planning for an earthquake scenario.

Despite the lack of population and behavioral factors in casualty prediction models, some of these factors are considered when predicting the size of displaced populations (i.e., requiring shelter) in the HAZUS loss estimation model. Integrating population and behavioral characteristics into loss estimation models could use similar methods as those that predict population displacement, thereby improving the accuracy of loss prediction models and providing better integration with displacement models.

5 Limitations

The process of predicting casualties in future earthquake events is highly complex and involves factors such as robustness of critical infrastructures, which were not considered in this study. The number of studies that used analytical methods to determine the risk factors related to the characteristics of the affected population and to medical preparedness is relatively low and disproportionately represented in regions with developed infrastructures. These results may not be directly generalizable to all earthquakes, but the body of evidence strongly supports the need to integrate population characteristics into prediction models for all regions.

6 Conclusions

This study provides evidence that integrates demographic and socioeconomic characteristics and levels of medical preparedness into existing casualty estimation models may refine the predicted outcomes and improve earthquake casualty estimation accuracy. In order to enhance preparedness and mitigate dire outcomes of future earthquakes, countries and regions depend on predictions and estimations of damage and casualties that are generated by loss estimation models. Hence, it is very important to estimate casualties as accurately as possible. This is a difficult and complex task, which requires considering many factors and therefore benefits by involving different disciplines (e.g., epidemiology and engineering). Public health agencies and other community or national organizations may consider using this information to allocate resources more adequately to enhance preparedness and mitigate future loss among vulnerable population groups.

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Conflict of interest The authors declare that they have no conflict of interests.

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