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An interdisciplinary perspective on social and physical determinants of seismic risk

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Abstract

While disaster studies researchers usually view risk as a function of hazard, exposure, and vulnerability, few studies have systematically examined the relationships among the various physical and socioeconomic determinants underlying disasters, and fewer have done so through seismic risk analysis. In the context of the 1999 Chi-Chi earthquake in Taiwan, this study constructs five hypothetical models to test different determinants that affect disaster fatality at the village level, namely seismic hazard intensity, population, building fragility, demographics and socioeconomics. The Poisson Regression Model is used to estimate the impact of natural hazards and social factors on fatality. Results indicate that although all of the determinants have an impact on the specific dimension of seismic fatality, some indicators of social inequality, such as gender ratio, dependency ratio, income and its SD, are the driving determinants deteriorating vulnerability to seismic risk. These findings have strong social implications for policy interventions to mitigate such disasters. This study presents an interdisciplinary investigation into social and physical determinants in seismic risk.

1 Introduction

Disaster studies is a growing field which integrates the natural and social sciences (Mileti, 1999; Tierney, 2007). Over the past few decades, our understanding of natural hazards has grown dramatically (IRDR, 2013; ICSU, 2010). Scientists can now more accurately characterize the possible magnitude of a given hazard, and estimate the possibility of its occurrence and potential exposure areas. However, far less known is about the interaction of natural hazards and human-made factors in terms of disaster losses (ISSC, 2013), and little empirical work of effective interdisciplinary collaboration has been done to examine the coupling of natural and social determinants underlying disaster impacts (McBean, 2012; ICSU, 2010).

Human action has long been understood to have an impact on disaster outcomes, and over the past few decades a rich literature has firmly recognized disaster as a process of social construction (Bankoff et al., 2004; Clark and Munn, 1986; Kasperson and Kasperson, 2005). Over time, the notion of vulnerability has gained increased emphasis in disaster risk studies, promoted by UNISDR and many other initiatives over the years (McCarthy et al., 2001; Cardona, 2012). In seismic studies, the application of the vulnerability approach has been expanded from a more limited interpretation on susceptibility assessments of the built environment (Calvi et al., 2006; Tyagunov et al., 2006) to more complicated modeling for risk assessment (Cardona et al., 2008). However, despite a few cross-national studies (Keefer et al., 2011; Lin, 2014) which do not really control for the magnitude of earthquakes, few empirical investigations have holistically examined the social and physical determinants underpinning seismic risk through an integrative risk formula. Thus this study presents a substantial attempt to integrate research from seismology, seismic engineering, geography and sociology to clarify the multidimensional driving forces underlying seismic risk.

This study takes an interdisciplinary and holistic perspective in investigating the physical and social determinants which lead to high seismic fatality risk. The risk assessment model proposed by IPCC (2012, 2014) is applied to the 1999 Chi-Chi (Taiwan) earthquake by integrating seismic, building, demographic and socioeconomic datasets at the village level. Statistical results of Poisson regressions demonstrate that seismic hazard in the form of ground shaking and ground failure; an exposure dimension controlled by the population; and vulnerability measured by building fragility, gender ratio, income and its SD are all critical determinants affecting disaster fatality in the villages in question. This interdisciplinary collaboration effectively sheds light on the role played by natural hazards and social factors in seismic risk.

2 Seismic risk

The development of modern risk analysis and assessment is closely linked to the establishment of scientific methodologies used to identify causal links between adverse effects and different types of hazardous events, and mathematical theories of probability (Cardona, 2012; Covello and Mumpower, 1985). However the terminology has not been defined uniformly across the various disciplines involved. In the natural sciences, risk is defined as the probability of an event occurring multiplied by its consequences (Thywissen, 2006). However, in the geosciences and multidisciplinary sciences, risk can also refer to the degree of potential loss due to exposure to hazards and the degree of social vulnerability (Rashed and Weeks, 2003). In the early 1980s, a report to the United Nations Disaster Relief Organization (UNDRO) treated risk as a function of hazard, exposure and vulnerability (UNDRO, 1980). But this conceptualization has received little attention because the concept of vulnerability was not adequately explored by the academic community until recently (Adger, 2006; Timmerman, 1981; Watts and Bohle, 1993) resulting in definitions proposed by the IPCC and disaster research community (IPCC, 2012, 2014).

Prior to the establishment of a solid literature on social vulnerability (Cutter, 1996), conventional approaches for analyzing seismic risk included the hazard approach and the building fragility and exposure approach. The former addresses the geological and physical characteristics of seismology (Wu et al., 2004) and the latter looks at the specific mechanisms surrounding building structures and seismology that underpins the causality of mortality (FEMA, 2010; Yeh et al., 2006). For decades, the latter approach was framed in terms of seismic damage or loss analysis (Calvi et al., 2006; Tyagunov et al., 2006), but this approach has a limited capacity to explain mortality. As a result, vulnerability studies were introduced to investigate socioeconomic determinants in risk fatality. The three approaches are briefly reviewed below.

2.1 Hazard perspective

Scientists usually use two crucial physical determinants to measure seismic hazard – ground shaking and ground failure (Yeh et al., 2006). Ground shaking is the direct result of wave propagation during an earthquake (Lay and Wallace, 1995). Increased ground shaking is expected in the region near the epicenter (Wu et al., 2002), in areas characterized by soft soil or in a basin (Wu et al., 2004). Accompanying widespread ground shaking, surface ruptures could damage structures due to ground failure, i.e., the fault rupturing to the surface, soil liquefaction, and the associated ground settlement and lateral spreading. For example, during the 1999 Chi-Chi earthquake, a surface rupture with displacement exceeding 8 m at the northern part of the Chelungpu Fault caused severe damage to buildings and infrastructure, including dams and bridges (Chen et al., 2001; Ma et al., 1999).

2.2 Exposure and building fragility perspective

Another conventional and significant approach to seismic risk assessment is to look at the specific mechanisms surrounding seismic hazard and building structure that underpin the causality of mortality, given the concept that earthquake-induced mortality is the complex result of a natural disaster combined with the failure of human-built structures at a given degree of seismic hazard. In the past decade, geographic information system-based software and methodologies have been developed for earthquake loss estimation, such as HAZUS in the US (FEMA, 2010) and TELES in Taiwan (Yeh et al., 2006). In these methods, seismic risk is treated as the occurrence (probability) of a seismic event, along with exposure of people and property to the event, and the consequences of that exposure.

Typically, buildings are categorized according to the model building types, seismic design levels, and the specific occupancy classes. In building fragility models, structures are mostly treated as general building stock, categorized according to different structural types, seismic behaviors and usages, and the models are developed according to the structural characteristics and damage evidence taken from the field (Yeh et al., 2006). The damage state (i.e., none, slight, moderate, extensive or complete) of each model building type can be evaluated according to the seismic design level, ground shaking and ground failure of a specific event. The empirical casualty and injury rates for different model building types and under various damage states are employed under the assumption that they are mostly caused by building damage and/or collapse. However, there are still broader factors from the social and human dimensions which mediate the impacts and outcomes of seismic risk in terms of the resulting mortality, but the specific method of mediation remains a critical question.

2.3 Vulnerability perspective as the social construction of risk

Vulnerability is widely referred to social processes which shape human and economic losses in disasters (Blaikie et al., 1994; Cardona, 2012; Aysan, 1993). In the social science literature of disaster, economic development may be the most critical determinant shaping socioeconomic vulnerability (Cutter, 1996). From the rational choice perspective, Kahn (2005) argued that for saving lives and valued property, the elite and citizens in developed countries have greater economic motivation to invest in disaster mitigation. By contrast, leaders in developing countries tend to allocate resources to the development-oriented sectors rather than for disaster preparedness (Keefer et al., 2011). This implies that countries, communities or households with higher income levels are more likely to invest in disaster mitigation.

Economic inequality is another frequently mentioned factor that determines socioeconomic vulnerability. Using country-level data, Anbarci et al. (2005) argue that increased economic inequality is negatively correlated with the likelihood of various income groups to agree on the distribution of the burden of preparedness, causing the rich to self-insure against disasters, while the poor are excluded. While some studies may suggest that disaster resilience is mostly formed at the community level (Aldrich and Sawada, 2012), most statistical analysis is still undertaken at a larger scale in terms due to the difficulty of acquiring sufficient data at the community level.

It is widely understood that the young and old are more likely to be affected by hazards (Donner and Rodríguez, 2008). For example, in Japan's 1995 Hanshin earthquake and 2011 Tōhoku earthquake and tsunami, the elderly respectively accounted for approximately 60 and 65 % of all victims, while the elderly only accounted for 11 and 25 % of the general population at the time of those two disasters (Khazai et al., 2011). In contrast, the Haiti's 2011 earthquake resulted in a relatively higher death toll among children as a result of that country's high poverty, high fertility rate, and younger demographics (CDC, 2011). These demographic vulnerabilities can be explained by a lack of disaster safety knowledge among children, and the physical limitations of the elderly, leaving them unable to avoid the negative impacts of hazards.

Gender is another important determinant of social vulnerability. A substantive literature has demonstrated that women are more likely fall victim to natural disaster than men because women generally tend to have lower incomes, are more politically and socially marginalized, or are more likely to live alone (Fothergill, 1996). In addition, social expectations that women will take responsibility for caring for children and the elderly increases women's vulnerability (Enarson, 1998).

The factors mentioned above comprise a complicated fabric of social processes presenting in forms of poverty (Cutter, 1996), inappropriate urban development (Pelling, 2003), increased socioeconomic inequality (Anbarci et al., 2005), and lack of social networks and social support mechanisms (Klinenberg, 2002) that strongly impact vulnerability irrespective of the type of hazard. This underscores that disaster is an outcome of human activity, transforming natural hazard into risk through processes that increase exposure and vulnerability (IPCC, 2012). However, due to existing barriers between academic disciplines, the three approaches of risk analysis present a distinct division for which research specificity is bounded by the various disciplines with little sophisticated integration between them. This study thus aims to merge these approaches as outlined below.

2.4 Hypothesis and model construction

The risk formula used in this study is adopted from UNDRO (1980) and IPCC (2012) and treats risk as a function of the compounding effects of hazard, exposure and vulnerability as follows:

$$\text{Seismic Risk} = \text{Seismic Hazard} \times \text{Exposure} \times \text{Vulnerability} \tag{1}$$

$$\begin{array}{c}\text{Seismic Risk}\\(\text{fatality})\end{array} = \begin{array}{c}\text{Seismic Hazard}\\ \left(\begin{array}{c}\text{ground shaking level}\\\text{surface rupture}\end{array}\right)\end{array} \times \begin{array}{c}\text{Exposure}\\(\text{population})\end{array} \times \begin{array}{c}\text{Vulnerability}\\ \left(\begin{array}{c}\text{demographic traits}\\\text{socioeconomic traits}\\\text{building fragility}\end{array}\right)\end{array} \tag{2}$$

In this equation, the dependent variable, seismic risk, is defined as the total number of fatalities induced by earthquake. The ground shaking level of the earthquake and surface rupture are taken into account as the imperative factors for seismic hazard. Exposure is the total population exposed to the seismic hazard, and vulnerability is defined as the demographic and socioeconomic factors that are likely to attenuate or aggravate the degree of injury or fragility of the exposed population to the earthquake. In this study, building is viewed as an important factor in the vulnerability dimension since quality of building structures may impact the degree of injury to the population exposed to the earthquake. This study thus hypotheses that seismic risk, denoted as fatality, is the complex outcome of the physical conditions of the seismic activity (hazard), total population (exposure), and the demographic and socioeconomic characteristics and building fragility (vulnerability). The hypothesis, along with the relationships among these factors, is thus examined in the following section using multiple datasets and regressions.

3 Empirical case: Taiwan's Chi-Chi Earthquake

3.1 Background

The Chi-Chi Earthquake struck at 01:47 (UTC+08:00) on 21 September 1999 and proved to be the largest and most devastating in Taiwan in decades. It took place in central Taiwan along a 90 km rupture in the Chelungpu Fault (Fig. 1). The M_L 7.3 (M_W 7.6) main shock and following aftershocks killed more than 2400 people and injured more than 11 000, mostly due to building damage or collapse (Uzarski et al., 2001). According to local governmental statistics, mortality was concentrated in Taichung County (1138 fatalities) and Nantou county (928). However it was found that the relationship between mortality and seismic hazard varies if the impacted area is examined at the village level. For example, our data indicates that SA03, the indicator of ground shaking, has a positive but relatively weak correlation with fatality (see Fig. 1). Wu et al. (2002, 2004) also demonstrated a lack of clear correlations between the factors of ground shaking and building collapses resulting in fatalities. These preliminary findings reveal the need for a broader investigation into factors from other socioeconomic aspects to understand the stimulus of seismic disaster risk.

At the time of the earthquake, the Central Weather Bureau's Taiwan Strong Motion Instrumentation Program (TSMIP) monitored around 650 free-field digital accelerograph stations, recording a wealth of digital ground motions data. These data, as compiled by (Lee and Shin, 2001) are used here to verify the proposed risk analysis approach.

3.2 Data and measurement

To test our hypothesis, we collected data from different sources, including strong motion records from the Central Weather Bureau, building (tax) data from Ministry of Finance, population data from Ministry of the Interior, socioeconomic data from the Ministry of Finance, and fatality data from Wang (2011). The unit of analysis in this study is the village, which is defined as the lowest administrative unit in Taiwan. However, demographic characteristics are analyzed at the township level due to the difficulty of collecting sufficient data at the village scale. Table 1 summarizes descriptive statistics for the selected variables.

The dependent variable in the model is the death toll in each village (Kahn, 2005; Keefer et al., 2011). This is a count variable, thus the Poisson Regression Model (Wooldridge, 2008) is applied statistically to test the hypothesis.

The independent variables are composed of several different dimensions, each consisting of various components. The hazard dimension measures the physical determinants, while the exposure dimension accounts for the total population in each unit exposed to the hazard, and the vulnerability dimension includes components for the building's seismic capacity along with demographic and socioeconomic attributes.

The seismic hazard dimension comprises two components: seismic intensity and surface rupture. This study uses spectral acceleration to measure seismic intensity as it is apparently more representative than PGA and PGV from the perspective of seismic risk (Wu et al., 2002, 2004). In seismology engineering, spectral acceleration is the response of a damped structure (i.e., a building) in terms of acceleration under strong motion excitation, and is modeled as a particle mass on a massless vertical rod having the same natural period of vibration as the type of building in question. It can be calculated from the time history of a ground acceleration record given the period of the building (typically with a 5 % damping ratio). Here, the seismic records of the spectral acceleration at 0.3 s (denoted as Sa03) are used (Fig. 1). Because the heavily affected areas are mostly suburban and rural areas around the Chelungpu Fault, the majority of buildings are low rise (1–3 stories) with a natural period of vibration of around 0.3 s. According to the seismic design code, Sa03 of 0.14g is approximately of peak ground acceleration around 0.056g. It is classified as Seismic Intensity IV by Central Weather Bureau, which suggests no damage will occur. This study thus considers 4502 villages with Sa03 greater than or equal to 0.14g during the earthquake.

In terms of fault crossing, the surface rupture of the Chelungpu Fault surveyed by Chen et al. (2002) is overlaid to identify the trail and distribution of the fault rupture. A village is coded 1 if this village is located on the Fault, whereas 0 if not.

The exposure dimension has only one component which aims to measure the total population in each village exposed to the hazard. The vulnerability dimension has three components: demographics, socioeconomics and building fragility. For the demographics component, the sex ratio and population dependency factors are used to analyze the village's demographic vulnerability. The overall sex ratio (i.e., male population divided by female) is 1.08, meaning that males outnumber females in the studied villages. The population dependency factor calculates the percentage of the population under 14 and over 65 years old. The average dependency ratio (i.e., the population dependent on the labor force) is around 0.45, and one SD ranges from 0.36 to 0.55. According to earlier empirical findings (e.g., Donner and Rodríguez 2008), a greater dependent population represents a higher degree of demographic vulnerability. Notably, these demographic variables are controlled in the analysis to proxy the effect of village size and to adjust the number of fatalities in each village.

The building fragility component is measured based on the percentage of buildings with low seismic capacity. A village with higher ratio of low seismic capacity buildings indicates that its buildings are more vulnerable. The seismic zonation and design force level can be classified based on the history of seismic design codes for the buildings. Similar to the HAZUS methodology (FEMA, 2010), buildings are categorized into four seismic design levels (high, moderate, low and pre-code) according to construction year and location. The floor area-based percentage of low seismic capacity buildings (i.e., pre-code and low-code buildings) for each village in 2000 is assessed using building tax data. Generally, the average percentage is 37 % among the studied villages.

Finally for the socioeconomic component of the vulnerability dimension, the factors of mean/median and SD of income are used to assess economic development and income inequality in a society (Kahn, 2005; Kellenberg and Mobarak, 2008). This operation is widely applied to represent the conception of socioeconomic vulnerability, using the logarithm of median household income before tax, which indicates the average socioeconomic standard of each village, and the SD of household income before tax which implies the extent of inequality within a given village. Overall, in the study the SD of household income before tax ranges from TWD 182 000 to TWD 2 370 000 (approx., USD 6000 to USD 62 000).

4 Results

Table 2 summarizes the results of the Poisson regression analysis for testing the seismic risk hypothesis in the Chi-Chi earthquake. To validate the relative importance of each parameter contributing to the seismic risk, we structured five regression models to isolate the impact of each factor on the death toll.

Model 1 estimates the impact of the seismic hazard, including Sa03 and surface-rupture, on the death toll in each village. The result shows that Sa03 is positively correlated to the number of fatalities, with an increase of 1.0 *g* of Sa03 resulting in 2.83 more deaths. Moreover, villages located on are found to incur 1.85 additional deaths as opposed to villages not on the fault.

Model 2 adds the factor and variable of population size on model 1, which is controlled to verify the relationship between population size and death toll in each village. A positive correlation is found, meaning that villages with larger populations will suffer more fatalities.

Model 3 adds the impact of building structure. After controlling the seismic hazard and population variables, villages with many low seismic capacity buildings are found to suffer 1.77 additional deaths as compared with villages without any low seismic capacity buildings. Villages with an average percentage of low seismic capacity buildings incurred an additional 0.65 deaths.

Model 4 tests the influence of sex ratio and dependent population on seismic fatalities. Not surprisingly, the results show that women are much more vulnerable than men, with villages with a 2 : 1 female/male gender ratio incurring an additional 2.1 fatalities. In addition, the dependent population, i.e., children and the elderly, is clearly more vulnerable to seismic risk, and children under 14 are found to have the highest vulnerability in the case of the Chi-Chi earthquake.

Finally, the socioeconomic variables regarding income and income inequality are tested in model 5. Higher income is found to be negatively correlated with seismic fatality, and villages in which the average monthly household income exceeds TWD 100 000 (USD 3300) incur 0.64 fewer fatalities. Similarly, greater income inequality is correlated with increased fatality risk on the basis that 0.01 more deaths would occur for each TWD 100 000 increase in household income. This model thus suggests that wealthy communities have lower risk of fatalities from seismic hazards, but that increased income inequality negates this effect and results in a net positive increase to fatality.

Based on the result of model 5, the relationships between the driving factors and each dependent variable are illustrated in Figs. 3–7. By controlling other variables in the model, Fig. 3 shows that an increase of 1g in Sa03 would result in three additional fatalities, while the number of fatality jumps eightfold for villages on the fault (Fig. 4). Figure 5 illustrates the striking impact of low seismic buildings on fatalities, and Figs. 6 and 7 present similar trends for income and income inequality.

5 Discussion and conclusions

Integrating research from seismology, seismic engineering, geography and sociology, this study seeks to examine and verify multi-dimensional driving forces (i.e., the physical, demographic, and socioeconomic determinants along with building fragility) which underlie seismic risk using the integrated risk formula developed by UNISDR in 1980 and then reframed by the IPCC (2012, 2014). Terms are carefully defined according to the specific domain knowledge in the relevant discipline, and factors used in the models are carefully selected based on a systematic literature review. The models were then applied to the case of the 1999 Chi-Chi earthquake in Taiwan to verify determinants in seismic fatality risk.

Five hypothetical models are built to test the varying determinants for outcomes of seismic fatality risk in the Chi-Chi earthquake: seismic hazard intensity for the hazard dimension; total population for the exposure dimension; and building fragility, demographic and socioeconomic components for the vulnerability dimension. The Poisson Regression Model is used to verify the models as it can treat the dependent variable (i.e., fatalities) as a count variable. Results indicate that all components have an explicit impact on the specific dimension for seismic fatality risk. Thus such risk cannot be regarded as simple physical or natural processes, but is an interactive construction of natural phenomena and social modification (Mileti, 1999).

Our study finds that vulnerability to seismic risk is increased for densely populated areas, disadvantaged populations (i.e., children, the elderly, and women), and in areas characterized by increased social stratification and inequality. It is important to emphasize that local social conditions and building structures are in place well before the disaster event, and thus institutional arrangements must be established to facilitate information exchange and cross-communication, and to institute policies to mitigate vulnerability (Kasperson and Berberian, 2011; Lin et al., 2011). Such policies could include efforts to promote for social development, welfare, and effective land planning, thus improving structural resilience, enhancing social networks and welfare systems, and reducing socioeconomic inequality. Such institutional designs and regulations are particularly important in communities which consistently face multiple natural hazards.

Understanding disaster risk management as a social process allows the focus to shift from disaster response toward disaster prevention (Cardona et al., 2012; Cardona and Barbet, 2000). Doing so requires deeper insight into patterns of human interactions with the natural environment, and how people, property, infrastructure and the environment are exposed to potential damage. In addition to natural conditions, this study demonstrates that skewed social development processes and inequality are important considerations for the construction of vulnerability. Also, vulnerability is potentially man-

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ageable by improving institutional arrangements. The present study represents a new direction in interdisciplinary collaboration to investigate the social and physical determinants of seismic risk. It is suggested that future studies examine the impact of additional social determinants (e.g., crime, social capital, and health) on seismic or other hazard risks, and that geographical information systems can be applied to analyze the socio-spatial effects of seismic risk variants.

References

Adger, W. N.: Vulnerability, Global Environ. Chang., 16, 268–281, 2006.

Aldrich, D. P. and Sawada, Y.: The Physical and Social Determinants of Mortality in the 3.11 Tsunami available at: http://ssrn.com/abstract=2421779 or doi:10.2139/ssrn.2421779 (last access: 7 April 2014), 2014.

Anbarci, N., Escaleras, M., and Register, C. A.: Earthquake fatalities: the interaction of nature and political economy, J. Public Econ., 89, 1907–1933, 2005.

Aysan, Y.: Vulnerability assessment, in: Natural Disasters: Protecting Vulnerable Communities, edited by: Merriman, P. A. and Browitt, C. W., IDNDR-Thomas Telford, London, 1–14, 1993.

Bankoff, G., Frerks, G., and Hilhorst, D.: Mapping Vulnerability: Disasters, Development and People, Earthscan, Sterling, VA, 2004.

Blaikie, P., Cannon, T., Davis, I., and Wisner, B.: At Risk: Natural Hazards, People's Vulnerability, and Disasters, Routledge, London, 1994.

Calvi, G. M., Pinho, R., Magenes, G., Bommer, J. J., Restrepo-Velez, L. F., and Crowley, H.: Development of seismic vulnerability assessment methodologies over the past 30 years, ISET J. Earthq. Technol., 43, 75–104, 2006.

Cardona, O. D., Ordaz, M. G., Yamin, L. E., Marulanda, M. C., and Barbat, A. H.: Earthquake loss assessment for integrated disaster risk management, J. Earthq. Eng., 12, 48–59, doi:10.1080/13632460802013495, 2008.

Cardona, O. D., van Aalst, M. K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R. S., Schipper, E. L. F., and Sinh, B. T.: Determinants of risk: exposure and vulnerability, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, USA, 65–108, 2012.

CDC: Post-Earthquake Injuries Treated at a Field Hospital – Haiti 2010, Morbidity and Mortality Weekly Report (MMWR) 59, Centers for Disease Control and Prevention (CDC), Atlanta, GA, available at: http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5951a1.htm 1673–1677, 2011.

Chen, W. S., Huang, B. S., Chen, Y. G., Lee, Y. H., Yang, C. N., Lo, C. H., Chang, H. C., Sung, Q. C., Huang, N. W., Lin, C. C., Sung, S. H., and Lee, K. J.: Chi-Chi Earthquake: a case study on the role of thrust-ramp structures for generating earthquakes, B. Seismol. Soc. Am., 91, 986–994, 2001.

Clark, W. C. and Munn, R. E.: Sustainable Development of The Biosphere, Cambridge University Press, Cambridge, 1986.

Covello, V. and Mumpower, J.: Risk analysis and risk management: an historical perspective, Risk Anal., 5, 103–120, 1985.

Cutter, S. L.: Vulnerability to environmental hazards, Prog. Hum. Geog., 20, 529–539, 1996.

Donner, W. and Rodríguez, H.: Population composition, migration, and inequality: the influence of demographic changes on disaster risk and vulnerability, Soc. Forces, 87, 1089–1114, 2008.

Enarson, E.: Through women's eyes: a gendered research agenda for disaster social science, Disasters, 22, 157–173, 1998.

FEMA: Hazus-MH MR5, Multi-hazard Loss Estimation Methodology, Earthquake Model Technical Manual Washington DC, available at: http://www.fema.gov/plan/prevent/hazus (last access: 15 January 2015), 2010.

Fothergill, A.: Gender, risk, and disaster, International J. Mass Emerg. Disast., 14, 33–56, 1996.

ICSU: Earth System Science for Global Sustainability: the Grand Challenges, International Council for Science, Paris, 2010.

IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, USA, 582, 2012.

IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the IPCC 5th Assessment Report – Changes to the Underlying Scientific/Technical Assessment, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 2014.

IRDR: Integrated Research on Disaster Risk Strategic Plan 2013–2017, Integrated Research on Disaster Risk, Beijing, China, 2013.

ISSC: World Social Science Report: Changing Global Environments, International Social Sciences Council, Paris, France, 2013.

Kahn, M. E.: The death toll from natural disasters: the role of income, geography, and institutions, Rev. Econ. Stat., 87, 271–284, 2005.

Kasperson, J. X. and Kasperson, R. E.: The Social Contours of Risk: Risk Analysis, Corporations and the Globalization of Risk, Earthscan, London, 2005.

Kasperson, R. E. and Berberian, M.: Integrating Science and Policy: Vulnerability and Resilience in Global Environmental Change, Earthscan, London, 2011.

Keefer, P., Neumayer, E., and Plümper, T.: Earthquake propensity and the politics of mortality prevention, World Dev., 39, 1530–1541, 2011.

Kellenberg, D. K. and Mobarak, A. M.: Does rising income increase or decrease damage risk from natural disasters, J. Urban Econ., 63, 788–802, 2008.

Khazai, B., Daniell, J. E., and Wenzel, F.: The March 2011 Japan earthquake: analysis of losses, impacts, and implications for the understanding of risks posed by extreme events, Technikfolgenabschätzung – Theorie und Praxis, 20, 22–33, 2011.

Klinenberg, E.: Heat Wave: a Social Autopsy of Disaster in Chicago, University of Chicago Press, Chicago, 2002.

Lay, T. and Wallace, T. C.: Modern Global Seismology, Academic Press, San Diego, 1995.

Lee, W. H. and Shin, T. T.: Strong-motion instrumentation and data, Earthq. Spectra Special Issue: Chi-Chi, Taiwan Earthquake, 17, 5–18, 2001.

Lin, K. H., Tsai, H. M., and Chang, C. Y.: Science and vulnerability reduction in Taiwan – cross-scale communication, knowledge co-production, and boundary organization after the 1999 Chi-Chi Earthquake, in: Integrating Science and Policy: Vulnerability and Resilience in Global Environmental Change, edited by: Kasperson, R. E. and Berberian, M., Earthscan, London, 233–268, 2011.

Lin, T.-H.: Governing natural disasters: state capacity, democracy, and human vulnerability, Social Forces, (forthcoming), available at: availableat:http://sf.oxfordjournals.org/content/early/2014/10/18/sf.sou104.abstract, 2014.

Ma, K. F., Lee, C. T., Tsai, Y. B., Shin, T. C., and Mori, J.: The Chi-Chi Taiwan earthquake: large surface displacements on an inland thrust fault, EOS, 80, 605–611, 1999.

McBean, G. A.: Integrating disaster risk reduction towards sustainable development, Current Opinion in Environ. Sustain., 4, 122–127, doi:10.1016/j.cosust.2012.01.002, 2012.

McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S.: Climate Change 2001: Impacts, Adaptation and Vulnerability, Cambridge University Press, Cambridge, UK, 2001.

Mileti, D. S.: Disasters by Design: a Reassessment of Natural Hazards in the United States, Joseph Henry Press, United States, 1999.

Pelling, M.: The Vulnerability of Cities: Natural Disasters and Social Resilience, Earthscan, London, 2003.

Rashed, T. and Weeks, J. R.: Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas, Int. J. Geogr. Inf. Sci., 17, 547–576, 2003.

Thywissen, K.: Core terminology of disaster risk reduction: a comparative glossary, in: Measuring Vulnerability to Natural Hazards, edited by: Birkmann, J., UNU Press, Tokyo, Japan, 448–496, 2006.

Tierney, K. J.: From the margins to the mainstream? Disaster research at the crossroads, Annu. Rev. Sociol., 33, 503–525, 2007.

Timmerman, P.: Vulnerability, Resilience and the collapse of Society, University of Toronto, Institute of Environmental Studies, Research Paper, Toronto, 1981.

Tyagunov, S., Grünthal, G., Wahlström, R., Stempniewski, L., and Zschau, J.: Seismic risk mapping for Germany, Nat. Hazards Earth Syst. Sci., 6, 573–586, doi:10.5194/nhess-6-573-2006, 2006.

UNDRO: Natural Disasters and Vulnerability Analysis, UNDRO, Geneva, Switzerland, 1980.

Uzarski, J., O'Rourke, M., Abrahamson, N., and Amin, N. R.: Introduction to Chi-Chi, Taiwan earthquake, Earthq. Spectra Special Issue: Chi-Chi, Taiwan Earthquake, 17, 1–3, 2001.

Watts, M. J. and Bohle, H. G.: The space of vulnerability: the causal structure of hunger and famine, Prog. Hum. Geog., 17, 43–67, 1993.

Wooldridge, J. M.: Introductory Econometrics: a Modern Approach, international edn. of 4th Edn., edited by: Mason, O. H., South-Western College, 2008.

Wu, Y.-M., Hsiao, N.-C., Teng, T.-L., and Shin, T.-C.: Near real-time seismic damage assessment of the rapid reorting system, TAO, 13, 313–324, 2002.

Wu, Y.-M., Hsiao, N.-C., and Teng, T.-L.: Relationships between strong ground motion peak values and seismic loss during the 1999 Chi-Chi Taiwan earthquake, Nat. Hazards, 32, 357–373, 2004.

Yeh, C. H., Loh, C. H., and Tsai, K. C.: Overview of Taiwan earthquake loss estimation system, Nat. Hazards, 37, 23–37, 2006.

Table 1. Descriptive statistics of selected variables.

$N = 4502$	Mean	SD	Min	Max	
Dependent Variable					
Fatalities	0.52	3.78	0	–	87
Seismic Hazard Variables					
Sa03(*g*)	0.36	0.27	0.14	–	1.86
Fault-influenced villages	0.03	0.17	0	–	1
Percentage of low seismic capacity buildings	0.37	0.21	0	–	1
Town-level Control Variables					
Population (10 000 people)	11.00	11.63	0.33	–	52.39
Sex ratio	1.08	0.07	0.94	–	1.35
Dependence					
Percentage of population under age 14	0.21	0.03	0.12	–	0.28
Percentage of population over age 65	0.09	0.03	0.04	–	0.19
Household Income before Tax (HIT) (TWD 100 000)					
ln (Median of HIT)	1.63	0.17	0.81	–	2.66
SD of HIT	6.68	8.82	1.82	–	237.35

Table 2. Determinants of fatalities in the 1999 Chi-Chi Earthquake: the poisson regression.

	Model 1	Model 2	Model 3	Model 4	Model 5
Seismic Hazard Variables					
Sa03(g)	2.83^{***}	3.04^{***}	3.25^{***}	3.32^{***}	3.31^{***}
	(0.05)	(0.06)	(0.06)	(0.06)	(0.06)
Fault-influenced	1.85^{***}	1.80^{***}	1.65^{***}	1.59^{***}	1.59^{***}
	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
Village Characteristics					
Population		0.02^{***}	0.02^{***}	0.01^{***}	0.01^{***}
(10 000 people)		(0.0026)	(0.0026)	(0.0038)	(0.0039)
Percentage of low			1.77^{***}	1.80^{***}	1.82^{***}
seismic capacity buildings			(0.12)	(0.12)	(0.12)
Sex ratio				-2.13^{***}	-2.58^{***}
				(0.64)	(0.71)
Dependence					
Percentage of population				4.24	5.65^{*}
under age 14				(2.17)	(2.23)
Percentage of population				3.33	4.82
over age 65				(2.38)	(2.54)
Household Income before Tax (HIT) (TWD 100 000)					
ln (Median of HIT)					-0.64^{***}
					(0.19)
SD of HIT					0.01^{***}
					(0.0021)
Intercept	-2.63^{***}	-3.00^{***}	-3.73^{***}	-2.62^{**}	−1.64
	(0.05)	(0.06)	(0.08)	(0.87)	(0.97)
N	4502	4502	4502	4502	4502
Log lik.	−5204.31	−5165.92	−5051.55	−5040.53	−5026.07

Standard errors in parentheses $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table A1. Correlation matrix of independent variables.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1)	Sa03(g)	1								
(2)	Fault-influenced villages	0.36*	1							
(3)	Percentage of low seismic capacity buildings	−0.21*	0.02	1						
(4)	Population (10 000 people)	−0.26*	−0.03	0.18*	1					
(5)	Sex ratio	0.18*	−0.02	−0.09*	−0.63*	1				
(6)	Percentage of population under age 14	−0.02	0.05*	0.20*	0.23*	−0.51*	1			
(7)	Percentage of population over age 65	0.16*	−0.03*	−0.24*	−0.59*	0.70*	−0.82*	1		
(8)	ln (Median of HIT)	−0.14*	−0.03	0.02	0.48*	−0.62*	0.25*	−0.36*	1	
(9)	SD of HIT	−0.07*	−0.02	0.01	0.21*	−0.29*	0.05*	−0.11*	0.42*	1

* Significant at 5 %, two-tailed tests.

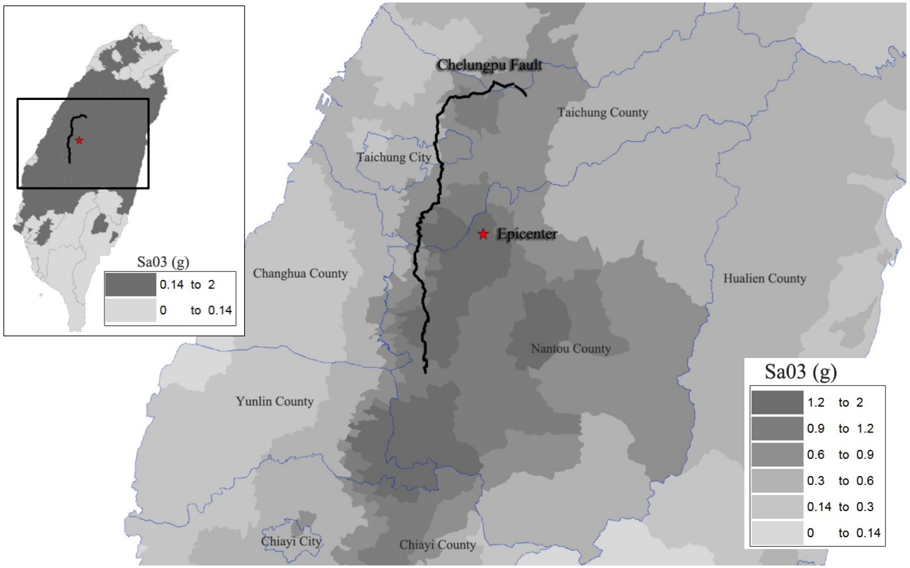

Figure 1. Epicenter, surface rupture of the Chelungpu Fault and distribution of seismic intensity of the 1999 Chi-Chi earthquake, Taiwan.

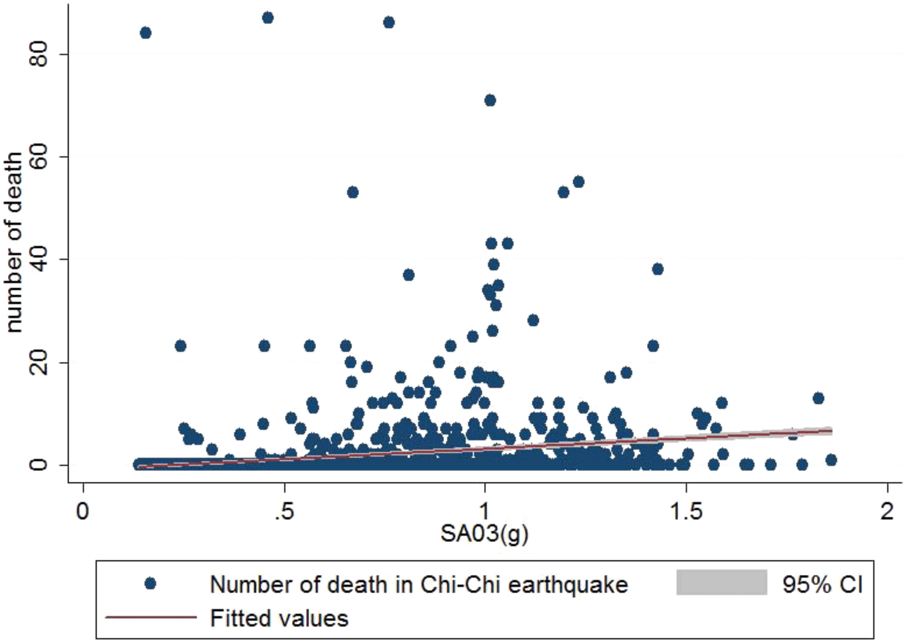

Figure 2. Magnitude and fatalities at the village level, Chi-Chi earthquake 1999.

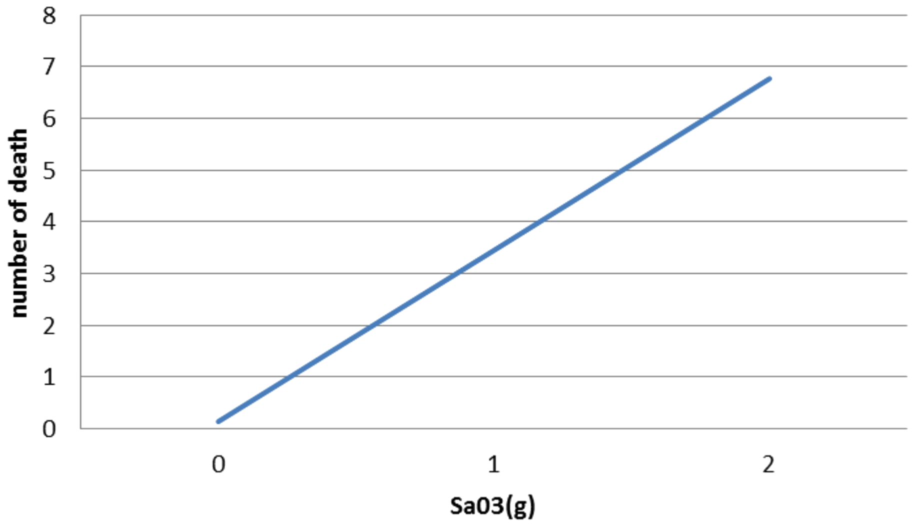

Figure 3. Sa03 and estimated fatalities (model 5).

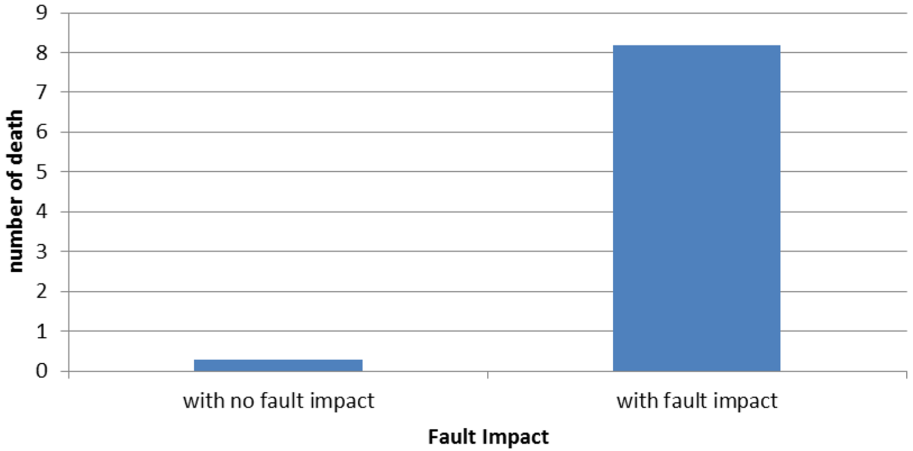

Figure 4. Fault crossing and estimated fatalities (model 5).

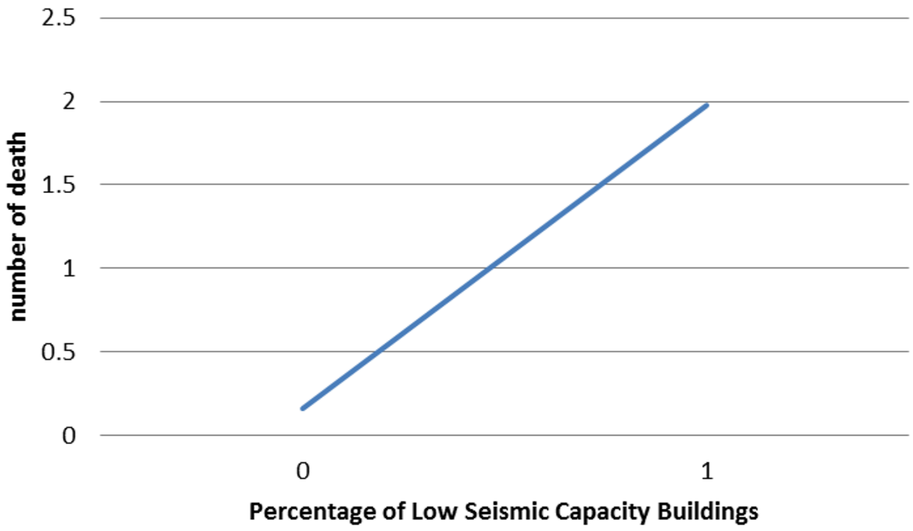

Figure 5. Low seismic capacity buildings (%) and estimated fatalities (model 5).

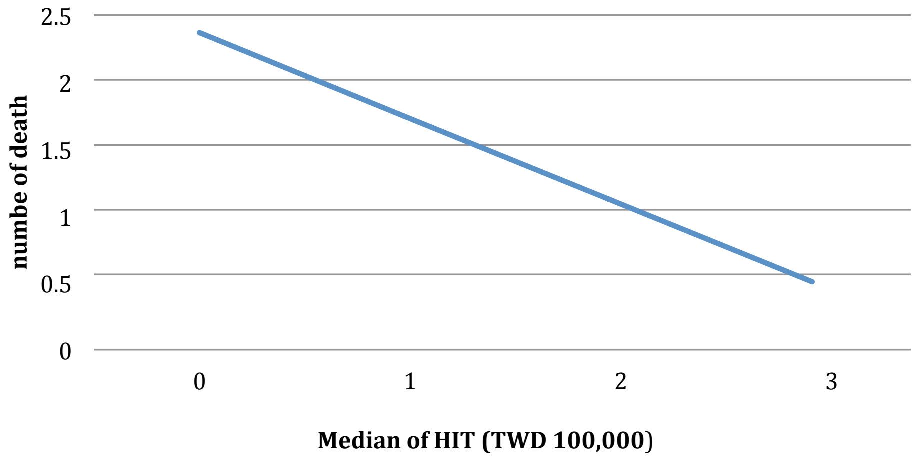

Figure 6. Median of HIT and estimated fatalities (model 5).

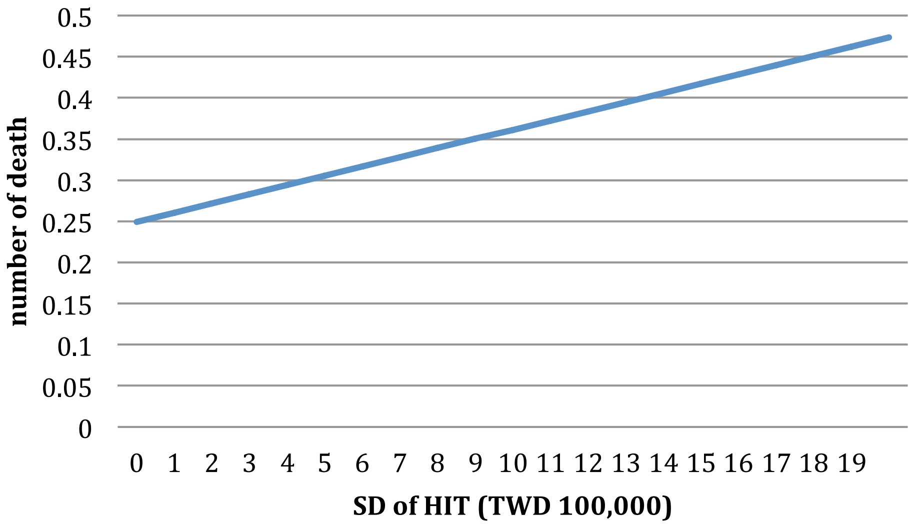

Figure 7. SD of HIT and estimated fatalities (model 5).