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 three statistical models to test different determinants that affect disaster fatality at the village level, including seismic hazard, exposure of population and fragile buildings, and demographic and socioeconomic vulnerability. The *Poisson* regression model is used to estimate the impact of these factors on fatalities. Research results indicate that although all of the determinants have an impact on seismic fatality, some indicators of vulnerability, such as gender ratio, percentages of young and aged population, income and its standard deviation, are the important determinants deteriorating seismic risk. These findings have strong social implications for policy interventions to mitigate such disasters.

Keywords: seismic risk, vulnerability, social inequality, Chi-Chi earthquake, Taiwan

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 IPCC, UNISDR and many other initiatives since 2000 (McCarthy et al., 2001;Cardona, 2012). Its application in seismic studies is also profound, ranging from a more limited interpretation on susceptibility assessments of the built environment (Calvi et al., 2006;Tyagunov et al., 2006) to a more complicated modeling for risk assessment (Cardona et al., 2008). However, despite a few cross-national studies (Keefer et al., 2011; Lin 2015) which do not exactly control for the magnitude of earthquakes, few empirical investigations have been made to holistically examine the social and physical determinants underpinning seismic risk through an integrative risk formula. This study 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 Intergovernmental Panel on Climate Change (IPCC) (2012, 2014) is applied to the 1999 Chi-Chi (Taiwan) earthquake by integrating seismic, building, demographic and socioeconomic datasets at village level. The *Poisson* regression model is used to estimate the effect of natural hazards and social factors on fatalities. Statistical results show that seismic hazard in the form of ground shaking and ground failure, exposure measured by population and fragile buildings, and vulnerability measured by gender ratio, percentages of young and aged population, income and its standard deviation (presenting income inequality) are all critical determinants affecting disaster fatality in the examined villages. This interdisciplinary collaboration effectively sheds light on the role played by natural hazards and social factors in seismic risk.

2. Progression of seismic risk studies

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 refers 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 at the time because the concept of vulnerability was not adequately explored by the academic community until quite recently (Adger, 2006;Timmerman, 1981;Watts and Bohle, 1993), resulting in the broad application of risk definitions across disciplines including IPCC and the disaster research community (IPCC, 2012, 2014).

Prior to the establishment of a solid literature on social vulnerability index (Cutter 1996), conventional perspectives for analyzing seismic risk include the seismic hazard perspective and the population-building exposure perspective. The seismic hazard perspective addresses the geological and physical characteristics of seismology (Wu et al., 2004). The population-building exposure perspective looks at the specific mechanisms surrounding building structures and seismic hazards that underpins the causality of mortality (FEMA, 2010a;Yeh et al., 2006). But these two approaches still have a limited capacity to explain mortality. For example, Wu et al. (2002, 2004) investigated the relationship between damage rate (fatality and house collapse rates) and seismic magnitude at the township scale, and found no obvious correlation among fatality, house collapse, and Peak Ground Acceleration (PGA) or Peak Ground Velocity (PGV). As a result, vulnerability studies were introduced to investigate socioeconomic determinants in earthquake fatalities. The three approaches are briefly reviewed below.

2.1 Seismic hazard perspective

The seismic hazard perspective usually considers two crucial physical determinants to measure the 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., 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 meters 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 Population-building exposure perspective

This perspective is widely used in seismic risk assessments. It studies the specific mechanism surrounding seismic hazards and building structures that underpin the causality, given the concept that earthquake-induced mortality is the complex outcome of a natural disaster combined with the failure of man-made environments. In the past decade, geographical information system-based software and methodologies have been developed and integrated in the analysis for earthquake loss estimation; some examples include the HAZUS Earthquake Model and Taiwan Earthquake Loss Estimation System (TELES). The HAZUS Earthquake Model

(FEMA, 2010b) was developed by U.S. Federal Emergency Management Agency (FEMA), while TELES (Yeh et al., 2006) was developed by the National Center for Research on Earthquake Engineering, Taiwan. Both models treat seismic risk as the occurrence (probability) of a seismic event, exposure of people and properties (usually buildings) to the event, and the consequences of that exposure.

In this approach, it is crucial to establish estimates of building damage. Buildings are first categorized to account for various structural types (model building type), seismic performance levels (coded seismic design level) and usage (specific occupancy class). Building fragility models are then developed according to the structural characteristics of any combination of model building type and seismic design level, and also according to the damage evidence collected in the field (Yeh et al., 2006). The severity of building damage can therefore be estimated by the extent of ground shaking and ground failure of a seismic event. The casualty and injury rates can be further calculated by using the empirical evidence of casualty and injury rates of certain damaged buildings, and also based on the model simulation of the population distribution in the buildings devoted to various usages (i.e., commercial buildings, schools, or residential buildings) and at different times (i.e., population distribution at 8am and 8pm are likely to have very different patterns).

The above presents an important progression of seismic risk studies from a hazard-oriented perspective towards one which considers how the built environment and population distribution mediate the impact of a physical event. The introduction of cross-disciplinary approaches has stimulated the integration of a vulnerability-oriented perspective in the analysis.

2.3 Vulnerability perspective

Vulnerability is widely referred to as social processes that shape human and economic losses in disasters (Blaikie et al., 1994;Cardona, 2012;Aysan, 1993). In the vulnerability literature, some factors have been widely identified as playing significant roles in the impacts of disasters. These factors include demographic characteristics (Cutter, 1996), poverty and income inequality (Anbarci et al., 2005), inappropriate urban development (Pelling, 2003), and the mechanisms involved in social networks and social support systems (Klinenberg, 2002). This perspective emphasizes that disasters are a social construction and an outcome of human activity that transforms natural hazard into disaster risk (IPCC, 2012).

In the social science literature of disaster, economic development may be the most critical determinant shaping vulnerability (Cutter, 1996). From the rational choice perspective, Kahn (2005) argued that politicians and citizens in developed countries have greater economic motivation to invest in disaster mitigation in an attempt to save lives and property. By contrast, leaders in developing countries tend to allocate resources to other political and development goals 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 vulnerability. Using country-level data, Anbarci et al. (2005) argue that increased income 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 suggest that the local community is one of the most crucial units for promoting disaster resilience or the establishment of social support systems to mitigate vulnerability (Aldrich and Sawada, 2012), most statistical analysis is still performed at the national, sub-national or municipal levels due to the difficulty of acquiring sufficient income distribution data at the community level.

The role of demography in disaster risk is also widely discussed. A great deal of research has revealed that the young and elderly 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 only accounting for 11% and 25% of the national 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 the 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 or reaction capacity 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 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 that are likely to influence fatality outcomes when a disaster strikes. However, barriers between academic disciplines have hindered the integration of these three perspectives of risk analysis, with each presenting a distinct view within which research specificity is bounded by the various disciplines. This study thus aims to merge these perspectives as outlined below.

2.4 Hypothesis and model construction

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

$$Seismic\ Risk\ = Seismic\ Hazard \times Exposure \times Vulnerability \quad (1)$$

$$\begin{matrix} Seismic\ Risk \\ (fatality) \end{matrix} = \begin{pmatrix} Seismic\ Hazard \\ ground\ shaking\ level \\ surface\ rupture \end{pmatrix} \times \begin{pmatrix} Exposure \\ population \\ fragile\ building \end{pmatrix} \times \begin{pmatrix} Vulnerability \\ demographic\ traits \\ socioeconomic\ traits \end{pmatrix} \quad (2)$$

In this study, 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 defined as the total population exposed to the seismic hazard and fragile buildings. This population-building exposure perspective conceptually views buildings as having an important impact on the degree to which the population is exposed to the seismic hazard. In other words, persons situated in fragile buildings with low seismic resistance would suffer from a higher degree of exposure from the doubling effect of the initial seismic hazard and the potential collapse of buildings. Following this concept, we thus define the exposure dimension as the exposure of population and fragile buildings to the hazard under the recognition that higher density of population and fragile building would increase the effect of exposure.

Vulnerability is defined as the demographic and socioeconomic factors that are likely to attenuate or aggravate the degree of fatality and injury of the population exposed to an earthquake. This study thus hypotheses that seismic risk, denoted as fatality, is the combined result of the physical conditions of the seismic hazard, population-building exposure, and 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 1:47 on September 21, 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 2,444 people (included 29 missing) 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 (1,138 fatalities) and Nantou county (928), which are relatively rural areas in Taiwan. During the earthquake, the Central Weather Bureau's (CWB) Taiwan Strong Motion Instrumentation Program (TSMIP) monitored around 650 free-field digital accelerograph stations, recording a wealth of digital ground motion data.

The data, as compiled by (Lee and Shin, 2001) are used here to verify the proposed risk analysis approach.

[Figure 1 HERE]

3.2 Data and Method

In order 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 analytical unit of this study is village, which constitutes the smallest administrative unit in Taiwan. However, demographic characteristics are analyzed at the township level due to the difficulty of collecting sufficient official demographic data at the village scale. Table 1 summarizes descriptive statistics for the selected variables. The simple correlations among the independent variables are provided in Table 2.

[Table 1,2 HERE]

The dependent variable in this study is the death toll in each village (Kahn, 2005; Keefer et al., 2011). This is a count variable, thus the *Poisson* regression model is applied to test the hypothesis. For a nonnegative counted integer, the simplest and most popular applied distribution is the *Poisson* (Agresti 2002, 7), the probability mass function of which is

$$\Pr(y) = \frac{e^{-\mu}\mu^{y}}{y!},\ y = 0, 1, 2, \ldots$$

This satisfies $E(Y)$ = var (Y) =μ. The *Poisson* distribution is used to account for events that occur randomly over time or space, when the outcomes in disjointed periods or regions are independent. If x_j is a vector of p independent variables, and the *Poisson* probability function can be presented as $E(Y|x) = e^{\sum_{j=0}^{p} \beta_j X_j}$. The model takes the logarithmic form $\log E(Y|x) = \sum_{j=0}^{p} \beta_j X_j$, which can be estimated by a maximum likelihood method of the General Linear Model (GLM). In our original models, the positive or negative coefficient β_j can be simply understood as the increase or decrease $\log E(Y|x)$ of death (Y) caused by the Chi-Chi earthquake when the independent variable X_j increases by one unit. The statistical result can be transferred back to an exponentiation relationship, which is positive correlation between X_j and the predicted incidence rate ratios E(Y|x), as shown in Table 3.

The independent variables include measurements from the three perspectives of seismic risk. The seismic hazard perspective comprises two variables: 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 second (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 seconds. 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 occur. This study thus considers 4,502 villages with Sa03 greater than or equal to 0.14g during the earthquake. As shown in Fig. 2, in the Chi-Chi earthquake, the records of seismic intensity (Sa03) correlated to fatalities, but alone can hardly explain the great variety of fatalities. 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.

[Figure 2 Here]

The population-building exposure perspective includes two variables which aim to measure the extent to which population and fragile buildings in each village are exposed to the hazard. The total township population data is applied to estimate population exposure. Building fragility is measured as the percentage of buildings with low seismic capacity. A village with higher ratio of low seismic capacity buildings indicates higher degree of building fragility. 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 the construction year and location. In this study, pre-code and low-code buildings are viewed as having low seismic capacity, and the floor area-based percentage of low seismic capacity buildings of all buildings in each village in the year 2000 is calculated using building tax data. Generally, the average percentage is 37% among the studied villages.

Several components of the vulnerability perspective are considered. The overall sex ratio (i.e., male population divided by female) is a measurement of the vulnerability of females within the population. For this study, the overall sex ratio is 1.08 on average, meaning that males outnumber females in the studied townships. The population dependency factor calculates the percentage of the population under the age of 14 and over the age of 65. A larger dependent population, either young or aged, indicates a higher degree of demographic vulnerability. Finally, for the socioeconomic component of vulnerability, the median and standard deviation of household income before tax are used to assess economic development and income inequality (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 economic development of each village, while the standard deviation of household income before tax reflects the extent of income inequality within a given village. Overall, in the study, the standard deviation of annual household income before tax ranges from TWD 182,000 to TWD 2,370,000 (approx., USD 6,000 to USD 62,000).

4. Results

Table 3 summarizes the results of the *Poisson* regression analysis for testing the seismic risk hypothesis in the Chi-Chi earthquake. The coefficient has been transformed back to the positive exponential relationship between each independent variable and the predicted incidence rate ratio. According to the *Poisson* function $e^{\beta_j X_j}$, if the coefficient equals 1, the variable is irrelevant to the incidence rate ratio on average. If the coefficient is greater than 1, *certeris paribus*, each unit of the variable has an exponential impact on the incidence rate ratio. However, *certeris paribus*, if the coefficient is smaller than 1, each unit of the variable reduces the incidence rate ratio in an exponential proportion.

[Table 3 here]

We estimated three regression models to illustrate the impact of the variables from the three perspectives 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 and positioning on the fault are positively correlated to the number of fatalities. By adding the variables of population size and building fragility, Model 2 shows significant coefficients for the variables to improve the model's robustness, i.e., the significance of the seismic hazard variable also increases. Based on Model 2, Model 3 further integrates vulnerability variables. Model 3 is our complete model that shows that most of the variables from the three perspectives significantly affect seismic fatality.

Based on the result of model 3, the seismic hazard is shown to be the most important factor in determining fatalities in the Chi-Chi earthquake. One unit of g increased in Sa03 could result in a 27.39-fold increase in fatalities in a village (mean = .52), *certeris paribus.* Having the fault cross the village resulted in a 4.92-fold increase. Because the seismic intensity is correlated to proximity to the fault (correlation=.36, please see Table 2), the interaction of the two variables is the major determinant of the fatality rate. Following the results of Model 3, Fig. 3 illustrates the exponential relationships between the seismic hazard variables and the predicted death toll. The result can be presented as the predicted death toll concentrated on two curves, the lower exponential curve without the fault, and the 4.92-fold increased exponential curve of the fault-influenced villages, as the seismic intensity Sa03 increased.

[Figure 3 HERE]

The result of model 3 also demonstrates a profound association between population-building exposure and fatalities. Each increase of 10,000 residents in a township could result in a one percent increase in fatalities, while increasing the ratio of low seismic capacity buildings from 0 to 100% results in a 6.17-fold increase in fatalities.

Finally the model shows that, although the impact of vulnerability may not be as significant as seismic hazard, it does contribute to earthquake fatalities. In our data set, the sex ratio falls in a range of 0.94~1.35. The coefficient implies that each 10% increase in a village's sex ratio can reduce fatalities by 9.2%. Although the coefficient for the percentage of population under age 14 rises to 284.18, its range is within 0.12~0.28 in the data set. That is to say, if the percentage increases from 0.12 to 0.22, it could lead to a 28.4-fold increase in fatalities. The coefficient of the percentage of population over age 65 (124.18) is also large but not significant. The problem of non-significance, however, might be due to the multicollinearity between the percentages of young and aged populations (correlation =-.82, see Table 2).

The standard of economic development, as measured by the logarithmic median household income before tax, effectively reduces the incidence of fatalities. For example, each unit increase of the variable, namely Log 1000 (Taiwanese dollars), from 1 to 2 could produce a 47% reduction in the death toll. In addition, there is a significant relationship between income inequality and fatalities. Each NTD 100,000 increase to the standard deviation of household income before tax (maximum NTD 237,350) could double the number of fatalities. Even though the impact of the vulnerability variables is smaller than those of seismic hazard or population and building exposure (and are difficult to express quantitatively), most coefficients are significant and match hypothetical expectations.

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 (IPCC 2012, 2014). Concepts are carefully defined and measurements used in the models are selected based on a systematic literature review of the three perspectives, namely seismic hazard, population-building exposure, and vulnerability. The *Poisson* regression models were applied to the case of the 1999 Chi-Chi earthquake in Taiwan to verify determinants in seismic fatality risk.

Three statistical models, considering seismic hazard, population exposure, and building fragility, demographic and socioeconomic vulnerability, are built to test the varying determinants for seismic fatality in the Chi-Chi earthquake. Results indicate that all components have an explicit impact on the specific dimension for seismic fatality risk. Thus such risk is regarded as an interactive construction of natural phenomena and social modification (Mileti, 1999).

Our study finds that seismic risk is increased in areas characterized by more fragile buildings, densely settled populations, a higher percentage of disadvantaged populations (i.e., children, the elderly, and women), reduced economic development and increased income inequality. It is important to reiterate that buildings and social conditions are in place well before the occurrence of any disaster event, thus much of the potential could be managed or alleviated through proactive intervention or disaster mitigation policies to reduce building fragility and vulnerability (Kasperson and Berberian, 2011;Lin et al., 2011). Such policies could include efforts to promote effective land planning and building regulations, strengthen structural resilience, enhance social networks and welfare systems, and reduce socioeconomic inequality. These institutional arrangements are particularly important in communities which consistently face natural hazards.

This study demonstrates the advantage of adopting an interdisciplinary perspective for the social and physical determinants of seismic risk. Future studies should examine the impact of additional social determinants (e.g., crime, social capital, and health) on seismic or other hazard risks, and geographical information systems can be applied to analyze the socio-spatial effects of seismic risk variables. Understanding disaster risk as an interaction between natural and social factors allows the focus to shift from disaster response toward disaster prevention (Cardona et al, 2012; Cardona and Barbet 2000). This implies that seismic risk could potentially be mitigated by an improved understanding of risk determinants along with improved institutional arrangements to reduce the risk.

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Table 1. Descriptive statistics of selected variables

N=4,502	Mean	SD	Min.~ Maximum
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 (dummy)	0.03	0.17	0~1
Exposure and Building Fragility Variables			
Population (10,000 people)*	11.00	11.63	0.33~52.39
Percentage of low seismic capacity buildings	0.37	0.21	0~1
Vulnerability Variables			
Sex ratio*	1.08	0.07	0.94~1.35
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
ln (Median of Household Income before Tax)	1.63	0.17	0.81~2.66
Standard Deviation of Household Income before Tax	6.68	8.82	1.82~237.35

Note: * Refers to the township level aggregative data.

Table 2 Simple correlations among 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

Note: * $p<0.05$, for the check of multi-collinearity among independent variables.

Table 3 Statistical models to estimate seismic fatalities in the 1999 Chi-Chi Earthquake: the *Poisson* regression

	Model 1	Model 2	Model 3
Seismic Hazard Variables			
Sa03(g)	16.91***	25.87***	27.39***
	(0.86)	(1.49)	(1.63)
Fault-influenced	6.33***	5.21***	4.92***
	(0.29)	(0.24)	(0.23)
Exposure and Building Fragility Variables			
Population (10,000 people)		1.02***	1.01***
		(0.003)	(0.004)
Percentage of low seismic capacity buildings		5.88***	6.17***
		(0.68)	(0.73)
Vulnerability Variables			
Sex ratio			0.08***
			(0.05)
Percentage of population under age 14			284.18*
			(634.01)
Percentage of population over age 65			124.18
			(315.56)
Ln (median household income before tax)			0.53***
			(0.10)
SD of household income before tax			1.01***
			(0.002)
Intercept	0.07***	0.02***	0.19
	(0.003)	(0.002)	(0.19)
N	4502	4502	4502
Log lik.	-5204.31	-5051.55	-5026.07

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

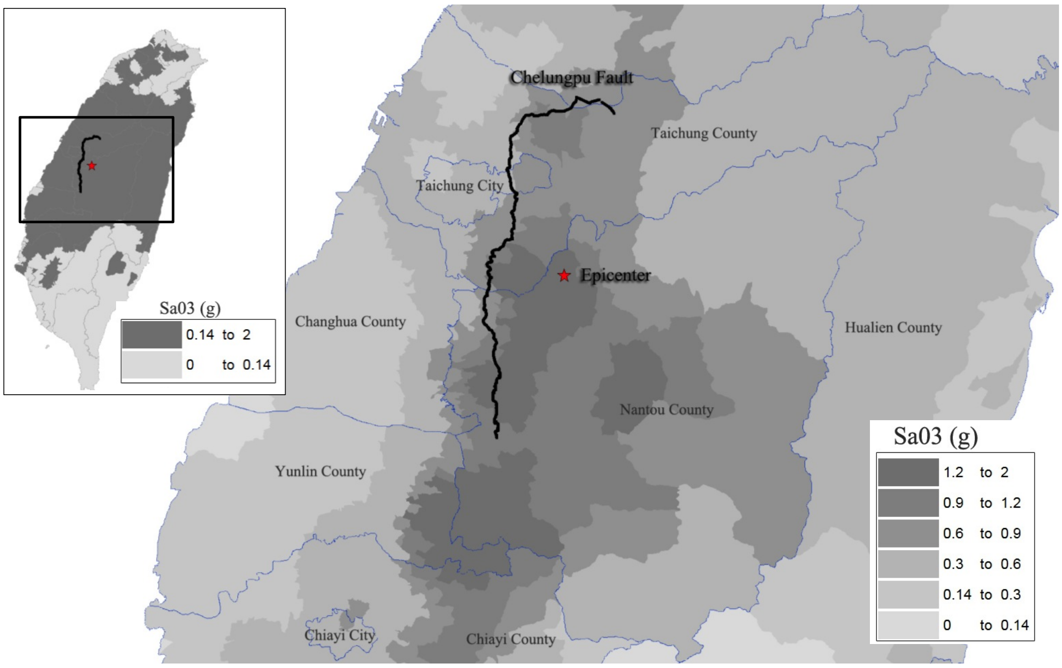

Figure 1. Epicenter, Chelungpu Fault and distribution of seismic intensity of the 1999 Chi-Chi earthquake, Taiwan.

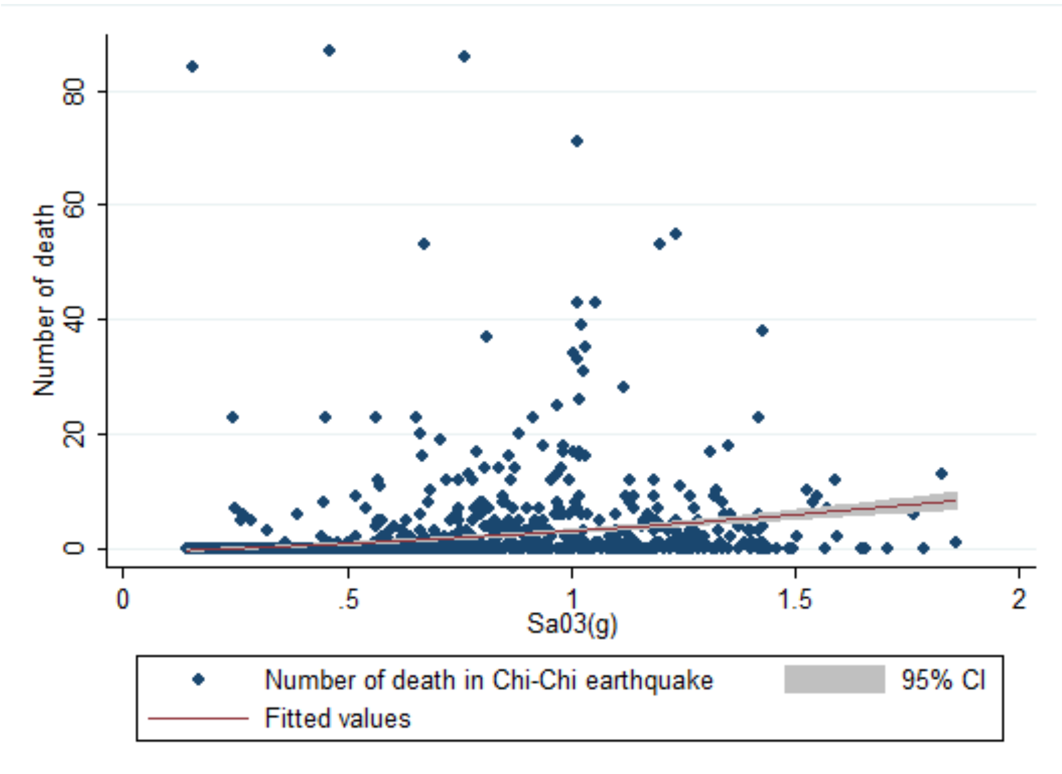

Figure 2. Sa03 and fatalities at the village level, Chi-Chi earthquake 1999. (Fitted in the exponential relationship between Sa03(g) and number of deaths)

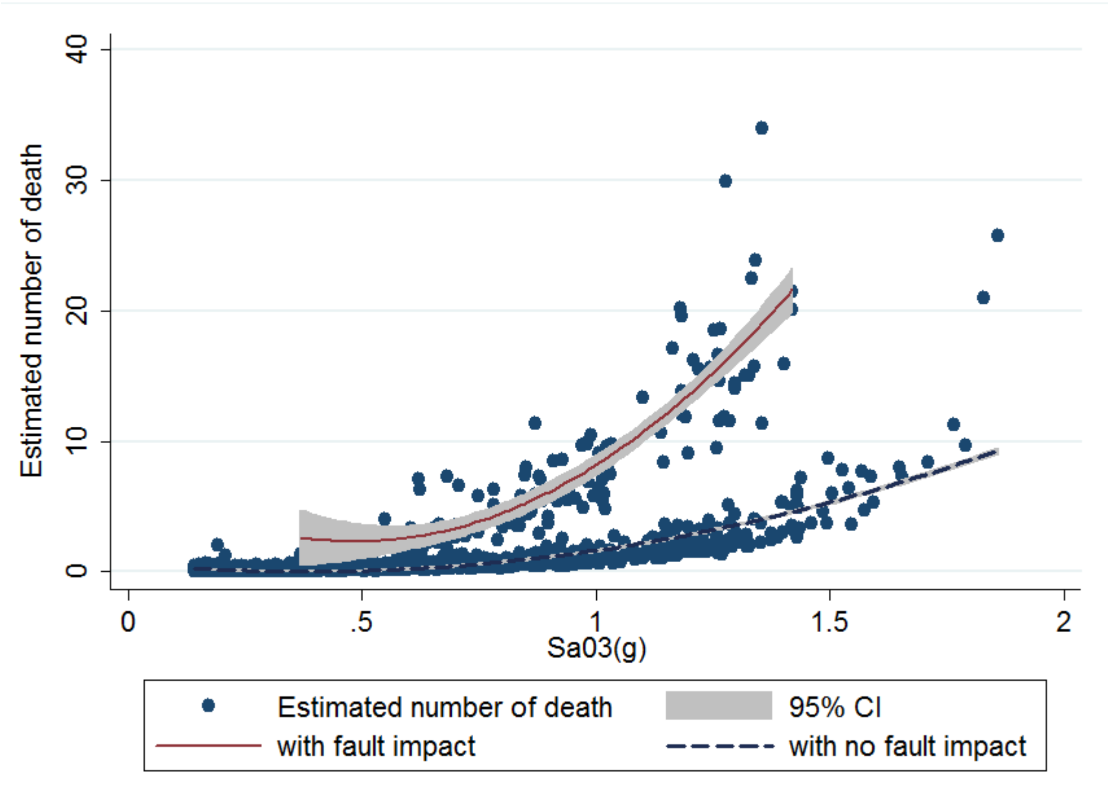

Figure 3. Sa03 and estimated fatalities by fault impact (model 3) (fitted in the exponential relationship between Sa03(g) and the estimated number of deaths by fault impact)