A Spatial Analysis of Casualties Sustained During the Chi-Chi Earthquake and its Applicability to Earthquake Casualty Modeling

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ABSTRACT

Earthquakes are by nature a spatial phenomenon. Seismic intensity and subsequent damage are directly related to the geographic properties of the affected area. This dissertation analyzes the spatial pattern of fatalities and hospitalized injuries sustained during the 1999 Chi-Chi earthquake in Taiwan. Seismic intensity, geographic properties such as soil type and distance to the epicenter, population density, building collapse, and demographic characteristics will be analyzed with respect to casualties in order to determine the spatial distribution of casualty risk. This research can be used to develop simple casualty models that predict the location of casualties to facilitate prevention of morbidity and mortality post-event and to assist in pre-event mitigation in order to mitigate the casualty risk from future earthquakes.

This dissertation develops earthquake casualty models centered on three different parameters and evaluates the predictive ability of these models. The maximum coseismic slip provides a better framework than either of the two commonly used spatial centering parameters: epicenter and surface rupture. The strengths and weaknesses of the coseismic slip methodology are further evaluated and additional predictive variables are incorporated into the model, including construction class and additional geologic data. This results in the development of construction class specific casualty vulnerability functions. The relationship between specific ground motion parameters and earthquake casualties is quantified and found to be in accordance with what would be expected from structural engineering research. Finally, a method for translating existing curves from past events to future earthquakes is introduced when the vulnerability functions derived from Chi-Chi are used to model a historical event, the 1976 Tangshan earthquake.

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CHAPTER 1 : INTRODUCTION

A large percentage of the world's population lives in areas with significant seismic risk. Many of the world's major population centers including Tokyo, Los Angeles, and Beijing are at risk for major earthquakes, which could result in tens or hundreds of thousands of casualties. The October 8, 2005 earthquake in Northern Pakistan killed at least 80,000 and injured over 100,000 people. The May 12, 2008 China earthquake currently has a death toll of 70,000 with thousands still missing. These events serve as an important reminder that earthquakes are a significant source of morbidity and mortality around the world. Earthquakes remain completely unpredictable; the only way to reduce their impact is through appropriate pre-event mitigation and effective post-event response and recovery.

Understanding the spatial pattern of casualties sustained during earthquakes is a concept that has been inadequately quantified, but one that is extremely important in response and recovery and mitigation. In response and recovery, spatial knowledge is paramount in urban search and rescue, the location of critical communications, and the storage and distribution of food, medical, and water supplies. For hazard mitigation, understanding the spatial pattern of casualties is vital in developing mitigation measures for critical infrastructure and adjusting regional growth and investments to minimize vulnerability. Recent catastrophes such as the South-Asian tsunami, Pakistani earthquake, and hurricane Katrina have highlighted the need for pre-event hazard mitigation and more effective post-event response and recovery.

A critical first step in reducing earthquake morbidity and mortality is establishing the spatial extent of the catastrophe. Rapid needs assessment is a vital initial step in disaster response and can minimize the inappropriateness of delays and content in aid and relief (Guha-Sapir, 1991). Needs assessment requires a set of tools that quickly allow for the prioritization of emergency services, search-and-rescue, and medical treatment that will minimize the loss of life. It has been shown that the probability of survival in the event of entrapment decreases rapidly with time (Murakami, 1996). In order to decrease extrication time it is paramount that rescue efforts be focused on areas where there are likely to be survivors.

Initial reconnaissance often includes rough estimates of the number of collapsed buildings, the presence of secondary hazards such as landslide and tsunamis, and ground motion data from sensors in place before the earthquake. Emergency managers are charged with making resource decisions based on limited information and census data.

A simple spatial relationship between faulting structures and casualties can be coupled with casualty vulnerability functions and building response research to develop better predictive models for future events and to more effectively respond to earthquakes. Understanding the spatial pattern of earthquake morbidity and mortality is helpful in loss estimation and in earthquake planning and response, specifically the distribution of resources both pre- and post-event.

The majority of earthquake-related research has focused on ground motion, building response, or individual-level epidemiology. A primary obstacle in emergency management is the lack of communication between disciplines and the lack of information disseminated in a useable format to the public and emergency managers. Complex attenuation functions, spectral response characteristics, and analyses of structural response have limited utility to emergency managers.

Programs such as the United States Federal Emergency Management Agency's (FEMA) loss estimation program, HAZUS, are designed for emergency managers. However, the casualty rates are simply multiples of building damage rates. Casualty models have historically been an afterthought of building engineering research projects. An alternative approach to earthquake casualty modeling is required to fulfill the needs of the public health community.

There is a need for a better structure to conceptualize and model the spatial pattern of earthquake fatalities in order to more accurately model events and increase the utility of spatial models in planning and response. By building seismologic principles into the base framework, a model can be created that will be applicable to complex faulting systems. Coseismic slip is the pattern of crustal movement that occurs during a seismic event. It is a key concept in understanding and modeling faulting structures. This dissertation will develop a distance-based spatial model using the maximum coseismic slip of the rupture as the centering point for an axial variation model.

In order to rapidly model loss there must be a quantitative framework for understanding ground motions and their impact on structural failure and casualties. Historically, intensity scales such as the Modified Mercalli Intensity (MMI) scale have been used to quantify ground motions. However, MMI is a descriptive measure determined in part by damage and observation. For this reason, inferences based on MMI are not generalizable. In addition, most areas of the world frequently affected by earthquakes now have strong-motion networks. Strong-motion data is a quantitative measure based on recorded instrumental intensities.

Casualty relationships and algorithms developed from strong-motion data would be quantitative, independent, and generalizable to areas with different building inventories and geologic substrates. In addition, the engineering community uses spectral response data in analyzing performance of structures. A shift towards using spectral acceleration in earthquake casualty modeling would allow for better and more accurate estimation of building response. It would also increase the ability to use engineering research in casualty modeling without first having to translate into a descriptive measure.

A primary component in reducing morbidity and mortality from earthquakes is understanding and characterizing the earthquake risk by building models upon which sound decisions can be made in a timely manner. Mathematical models are important tool in quantifying casualty risk and traditional post-event individual-level epidemiology is an important step in understanding factors leading to earthquake casualties. Significant effort has been made by seismologists, geologists, and engineers to characterize the earthquake risk, but similar rigorous modeling has not been extended to casualties. This dissertation begins to close the gap between geologic and epidemiologic models by developing distance-based and ground motion-based methodologies for spatial modeling of earthquake casualty risk and applying these methodologies in order to create casualty risk maps and vulnerability functions for the 1999 Chi-Chi and 1976 Tangshan earthquakes.

CHAPTER 2 : LITERATURE REVIEW

Earthquakes are the most unpredictable and potentially devastating of natural disasters. They are caused by a sudden release of energy that has built up in tectonic collisions. When plates become locked and are unable to gradually shift past each other, energy builds until the plates finally break free causing seismic waves to propagate. The United States Geological Survey (USGS) estimates that several million earthquakes occur each year, although the vast majority go undetected due to small magnitude or remote location. The National Earthquake Information Center detected and average of 27,000 earthquakes annually worldwide (National Earthquake Information Center, 2005).

The threat of catastrophic earthquakes has increased significantly with urbanization. In the past, no major earthquake has had its epicenter in an area with high population density. Many of the world's major population centers like Tokyo, Mexico City, San Francisco, Istanbul, and Calcutta are at risk for major earthquakes. It is just a matter of time before there is a large seismic event in a major population center.

2.1 Quantifying Earthquakes

2.1.1 Magnitude

The ground motion and energy produced by an earthquake is measured on a logarithmic scale, called the Richter scale. The Richter scale measures the maximum amplitude of the s-wave, or shear wave, which causes ground motion perpendicular to the propagation of the wave and therefore has easily measurable amplitude. An increase of

1.0 on the Richter scale corresponds to a tenfold increase in s-wave amplitude and an increase of 32 times in energy released. The Richter scale is the primary measure used to classify earthquake events. The relationship between magnitude and earthquake classification is as follows: Great 8.0 or higher, Major 7 - 7.9, Strong 6 - 6.9, Moderate 5 - 5.9, Light 4 - 4.9, Minor 3 - 3.9. The relationship between magnitude and earthquake strength along with an estimate of annual frequency is shown in Table 2-1.

Table 2-1: Richter Scale of Earthquake Magnitude

Earthquake Magnitude Scale		
Magnitude	**Earthquake Effects**	**Annual Estimated Number of Events***
2.5 or less	Usually not felt. Can be recorded by seismograph.	1,000,000
2.6 to 4.5	Often felt. Causes minor damage.	30,000
5.5 to 6.0	Slight damage to buildings and other structures.	500
6.1 to 6.9	Potential for a lot of damage in populated areas.	100
7.0 to 7.9	Major earthquake. Serious damage and casualties.	20
8.0 or greater	Great earthquake. Potential to totally areas near the epicenter.	1
* Numbers estimated from USGS National Center for Earthquake Information		

2.1.2 Intensity

Although the Richter scale effectively quantifies ground motion and energy released from an earthquake, it is an insufficient measure to assess an earthquake's destructive impact. An earthquake's impact is dependent on a number of geological factors including depth of earthquake origin, geological foundation of the site, distance from the epicenter, and shaking duration. In addition to the magnitude-based Richter scale, earthquakes are also classified on an intensity scale. Several different intensity scales exist including the Rossi-Forel, European Macro-seismic Scale (EMS), Medvedev-Sponheuer-Karnik (MSK), Omori (common in Asian countries), and the Modified Mercalli Intensity (MMI) Scale, which is typically used in the United States.

The MMI and EMS scales have no mathematical basis and use a system of 12 roman numerals assigned on observed effects. They are a qualitative assessment based on human observation, building response, and ground failure processes. Intensity varies spatially and although an earthquake will be assigned a single magnitude the intensity will vary based on the factors discussed above. The EMS scale is more strongly based on the behavior of structures than the MMI, although geologic and human effects are also taken into consideration. Advancements in structural engineering have caused the EMS scale to change over time and now a stronger ground motion may be required to reach a certain intensity than was required historically (Coburn, 1992). Figure 2-1 contains an intensity map of the Chi-Chi earthquake based on MMI intensity scale and Table 2-2 contains the MMI and EMS intensity scales.

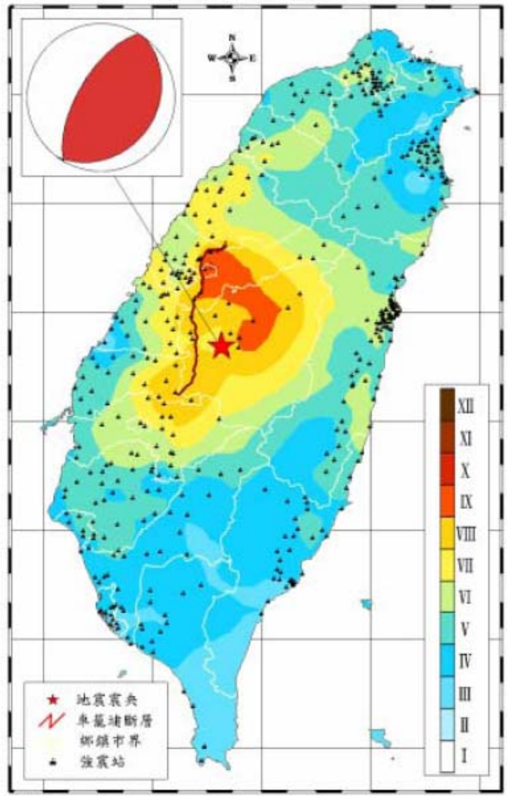


Figure 2-1: MMI Map of the 1999 Chi-Chi Earthquake, Taken From Liau, 2002

Table 2-2: MMI and EMS Intensity Scales

Modified Mercalli Scale and European Macro-seismic Scale		
Intensity value and description		
	Modified Mercalli Scale	**European Macro-seismic Scale**
I	Not felt except by a very few.	Not felt, even under the most favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration	The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.

	estimated.	
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.	The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.
V	Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.	The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top heavy objects topple over. Doors and windows swing open or shut.
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight.	Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings e.g.; fine cracks in plaster and small pieces of plaster fall.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stack, columns, monuments, walls. Heavy furniture	Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.

	overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed.	
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks.	Many ordinary buildings collapse.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.	Most ordinary buildings collapse.
XII	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into the air.	Practically all structures above and below ground are heavily damaged or destroyed.
	Adapted from Bolt, 1993	Adapted from Grünthal, 1998

The Japanese Meteorological Agency Scale (JMA Scale) was developed based on the first intensity scale proposed in the early part of the 20th century by Omori. The JMA scale is a seven-point scale based on the behavior of Japanese structures and is used only in Asian countries. It is similar to the MMI scale, except for that it does not quantify the lower intensity levels. Level I of the JMA scale is approximately equivalent to level VI in the MMI or EMS scale. The JMA scale is shown in Table 2-3: Japanese Meteorological Agency Intensity Scale

Table 2-3: Japanese Meteorological Agency Intensity Scale

	JMA Scale
I	Shock induces people to escape from their houses into the open. The walls of badly constructed brick houses crack slightly and some parquet falls down; ordinary wooden houses are shaken in such a degree that they loudly creak; furniture is overturned; trees are visibly shaken; the water in ponds and pools gets turbid; pendulum clocks stop; some very badly built factory chimneys are damaged.
II	The walls in the wooden houses of Japan crack; old wooden houses get slightly out of plumb; the Japanese tombstones and the badly constructed stone lanterns are overturned; in a few cases the flow of the thermal and mineral springs is changed; ordinary factory chimneys are not damaged.
III	About one-fourth of the factory chimneys are damaged; badly constructed brick houses are partially or totally destroyed; some old wooden houses are destroyed; wooden bridges are slightly damaged; some tombstones and stone lanterns are overturned; Japanese sliding doors are broken; the tiles of wooden houses are displaced; some fragments of rocks are detached from the sides of the mountains.
IV	All factory chimneys are ruined; the majority of the ordinary brick houses are partially or totally destroyed; some wooden houses are totally destroyed; the wooden sliding doors are mostly thrust out of their channels; crevices from 2 to 3 inches (5 to 7-1/2 cm) wide appear in low and soft grounds; here and there the embankments are slightly damaged; wooden bridges are partially destroyed; ordinarily constructed stone lanterns are overturned.
V	All ordinary brick houses are very seriously damaged; about 3 percent of the wooden houses are totally destroyed; some Buddhist temples are ruined; the embankments are badly damaged; the railways are slightly contorted; ordinary tombstones are overturned; brick walls are damaged; here and there, large fissures from 1 to 2 feet (30 to 60 cm) wide appear along the banks of the watercourses. The water of rivers and ditches is thrown on the banks; the contents of the wells are disturbed; landslides occur.
VI	The greater part of the Buddhist temples are ruined; from 50 to 80 percent of the wooden houses are totally destroyed; the embankments are almost destroyed; the roads through paddy fields are ruined and interrupted by fissures in such a degree that traffic by animals or vehicles is impeded; the railways are very much contorted; great iron bridges are destroyed; wooden bridges are partially or totally damaged; tombstones of solid construction are overturned; fissures some feet wide appear in the soil, and are sometimes accompanied by jets of water and

	sand; iron or terra cotta tanks embedded in the ground are mostly destroyed; all low-lying grounds are completely convulsed horizontally as well as vertically in such a degree that sometimes the trees and all the vegetation on them die off; numerous landslides take place.
VII	All buildings are completely destroyed except a few wooden constructions; some doors or wooden houses are thrown over distances from 1 to 3 feet; enormous landslides with faults and shears of the ground occur.
	Taken From Montel, 1912.

2.1.3 Instrumental Intensity

Historically, the use of intensity scales was important because no instrumentation was available and it allowed for a somewhat quantitative framework for observations of damage. Measures such as MMI are descriptive determined by damage and observation. The observational nature of intensity scales such as MMI make it so measurements are not consistent between regions with different building stocks and propensity for earthquakes. For this reason, inferences based on MMI have limited generalizabilty. Most areas of the world frequently affected by earthquakes now have instrumental methods to record ground motion. Strong-motion data is a quantitative measure based on recorded instrumental intensities. Strong-motion networks are series of digital accelerographs that record ground motions. From these records the response spectra (SA), peak ground acceleration (PGA), and peak ground velocity (PGV) can be calculated.

PGA most closely represents the ground motion experienced by a particle or an individual on the ground during an earthquake. The force of the earthquake is related to the magnitude of the ground acceleration. PGA is a simple design parameter since it is related to force and can be conceptualized as the resist of a structure to a certain horizontal force. The peak acceleration is the maximum acceleration during the entire course of an earthquake. Figure 2-2 shows two sample response spectra for the Chi-Chi earthquake: PGA for TCU068 is 1.5g and PGA for TCU071 is 2.25g. PGA typically occurs in the short period spectra under 0.5 seconds. For that reason it is often not well correlated with building damage and casualties. PGA can be a good parameter for low-rise buildings with stiff construction because the natural period of the building is likely to 0.5 seconds or less.

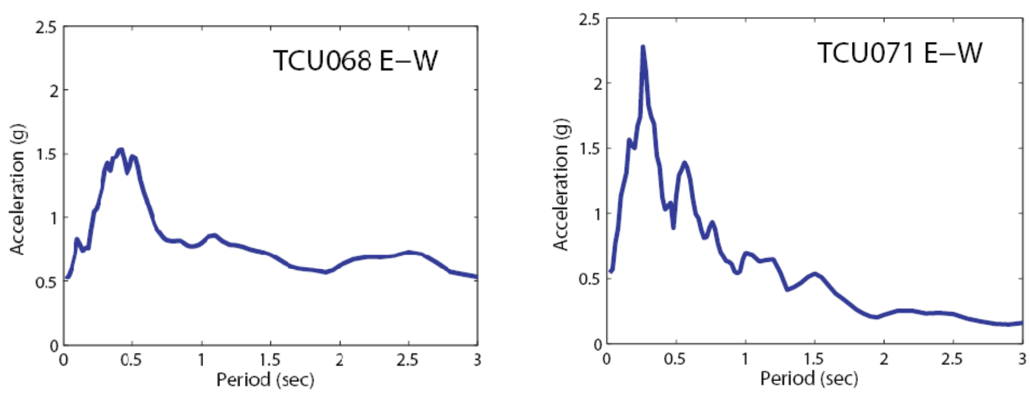


Figure 2-2: Sample Response Spectra from the 1999 Chi-Chi Earthquake

Spectral acceleration or spectral response (SA) is approximately what is experienced by a building. It is the maximum acceleration of a damped, single-degree-of-freedom harmonic oscillator. The maximum displacement at each period is recorded to get a response spectrum as shown in Figure 2-2. The response spectrum is a record of the amount of energy at different periods. Structural damage will be greatest when high levels of ground acceleration match the natural period of the building. Periods much shorter or much longer than the natural period of the building are unlikely to significantly damage the structure. A specific spectral value or spectral period will be the best indicator of building damage. The characteristics of the building including height, footprint size, and building material determine what the response period. Low-rise buildings constructed out of stiff materials such as masonry or concrete will have short natural periods. Tall buildings, or those constructed out of softer material like adobe, will have longer natural periods. Spectral acceleration records from an earthquake require a baseline correction to remove noise contamination and the effects of frequency-dependent instrument response before the records can be used.

Peak ground velocity (PGV) can be derived from the response spectrum. PGV most closely relates to SA values of around 1.0 seconds. PGV relates much more closely to longer period values and is a better parameter for looking at damage in tall building or softer building materials.

PGA, PGV, and SA are only approximately related to building response because structures are not simple oscillators. Different parts of the structure may have their own weaknesses. Structural modifications may change the natural period of the building. In addition, the duration of shaking plays a role in damage, and duration is not well-represented by response parameters. The non-linear response of a structure is only weakly dependent on the magnitude and distance. This means that the non-linear response can be correlated to the SA, but not to PGA or PGV. Therefore, SA should be the most appropriate parameter for correlating ground motion with structural damage and subsequently casualties.

2.2 Historical Context for Earthquake Impacts

The risks from an earthquake are multi-factorial and understanding them is significantly more complicated than knowing magnitude or intensity. Earthquake casualties can be a result of direct impacts, secondary impacts, and indirect impacts. Direct impacts include building or structural collapse, falls, shaking related traffic accidents, exit injuries, and injuries from non-structural hazards. Secondary impacts can be significantly more severe than direct impacts as demonstrated by the fires in the 1906 San Francisco earthquake and the tsunami in the 2004 Sumatra earthquake and include fire, landslides, tsunamis, floods, and hazardous materials releases. Indirect impacts include respiratory and cardiovascular complications and psychological symptoms, which may be seen well after the acute effects have subsided.

In order to appropriately evaluate the risk from an earthquake, factors such as population size and demographics, building materials, design, and construction, and mitigation measures must be considered. The data from post-event epidemiologic analyses must be applied to assessing risk and developing models to understand and mitigate the risk prior to the event and assist with post-event recovery.

Earthquakes have been recorded throughout history, but not until recently have the natural causes been understood. The earliest descriptive account of an earthquake was from China in 1187 B.C. (Shedlock, 1997). Large earthquakes have occurred with relative frequency. In the past five centuries, the death rate from earthquakes has averaged 100,000 per year, with this figure being dominated by infrequent catastrophic earthquakes (Bilham, 1995). Currently, over one billion people live in seismically active areas and that number can only be expected to increase with rapidly increasing population growth and urbanization.

The global threat from earthquakes over the last century is outlined in Table 2-4. Twelve of the top 50 most expensive natural disasters of the last century have been earthquakes. Despite numerous efforts at earthquake prediction, they remain unpredictable and the potential for instantaneous large-scale damage and loss of lives makes them formidable.

Table 2-4: Summary of the Impact of Historical Earthquakes

Summarized Table of Earthquakes sorted by Continent from 1901 to 2005							
	# of Events	Killed	Injured	Homeless	Affected	Total Affected	Damage $ (000's)
Africa	63	21,025	59,155	891,784	697,863	1,648,802	10,992,970
avg. per event		334	939	14,155	11,077	26,172	174,492
Americas	227	195,739	445,786	3,515,314	20,807,961	24,769,061	42,952,440
avg. per event		862	1,964	15,486	91,665	109,115	189,218
Asia	447	1,302,189	831,280	7,010,008	52,795,273	60,636,561	174,512,072
avg. per event		2,929	1,870	15,404	118,314	135,588	393,045
Europe	212	363,830	142,247	2,095,422	7,266,818	9,504,487	78,214,516
avg. per event		1,716	671	9,884	34,277	44,833	368,936
Oceania	37	438	767	19,620	67,574	87,961	2,509,419
avg. per event		12	21	530	1,826	2,377	67,822

EM-DAT: The OFDA/CRED International Disaster Database, Université catholique de Louvain, Brussels, Belgium, Data from 10/8/2005 Pakistan earthquake not included

The predominant factor in decreasing earthquake morbidity and mortality over the last century is advancements in structural engineering. In the 1940's engineers began adopting building practices to mitigate the structural hazards from earthquakes. Initially, because building dynamics were poorly understood the seismic hazard was underestimated. Data gathered from subsequent events caused the building codes to be revised to reflect developments in seismic engineering (Holmes, 1998). The threat of structural collapse in developed countries has been significantly reduced due to advances in engineering and materials science. Unfortunately, these technologies have not been implemented in developing countries and structural collapse remains a significant factor in earthquake morbidity and mortality.

2.3 Disaster Epidemiology

Disaster epidemiology is built on the principle that morbidity and mortality can be significantly reduced given appropriate preparedness and response. Historically, disaster epidemiology focused on rapid needs assessment after an event has occurred. Over the past few decades, it has become clear that prevention and preparedness are the most effective means of reducing the impact of disasters. The United Nations adopted “a more holistic approach that emphasizes vulnerability and risk factors, [which] has coalesced around the concept of risk reduction, or disaster risk management” (United Nations, 2004). This view of disaster risk emphasizes the need for research, including sound epidemiology and risk modeling in order to appropriately tailor preparedness messages and response capabilities.

The first use of epidemiologic assessment in a disaster situation was in 1957 when Saylor and Gordon suggested treating disasters as epidemics and utilizing the well defined parameters of time, place, and person (Noji, 1997a). In the 1960s, Center for Disease Control (CDC) workers began using epidemiologic principles in order to coordinate relief efforts. However, it was after a series of major worldwide disasters affecting Peru, Nicaragua, and Bangladesh in the early 1970s that the importance of disaster epidemiology in casualty prevention and effective response became clear (Noji, 2002). Practitioners of disaster epidemiology were faced with a number of difficulties in performing epidemiologic assessments during and immediately post disaster situations. These issues include the difficulty of obtaining reliable morbidity, mortality, and population estimates, lack of infrastructure and personnel, lack of time for standard epidemiologic methodology, political, cultural and physical barriers, and the fact that every disaster situation is different and poses a unique set of challenges.

In 1976, Michel Lechat, of the Centre for Research on the Epidemiology of Disasters, proposed dividing disaster epidemiology into three phases: pre-impact, impact, and post-impact or long-term. Pre-event epidemiology focuses on understanding hazards and vulnerability, as risk is a product of those two elements. This can include attempting to quantify and predict the risk by evaluating causes, frequency, and effects of past events. Some hazards, such as earthquakes, occur on geologic time scales there is often no data indicating the hazard exists until an event occurs. Some earthquake events occurring on previously unknown faults include the Assam Earthquake of 1897, the 2002 Denali earthquake, and the 1994 Northridge Earthquake, which had magnitudes of 8.0, 7.9, and 6.7 respectively (Thatcher, 2001; Fuis, 2003; Lockridge, 1997). The Northridge earthquake produced the strongest ground motions recorded in an urban setting and gave an indication of the destructive potential of earthquakes in highly populated areas.

The other component of pre-event assessment is vulnerability analysis. This includes political, social, economic, and personal processes that determine how an individual or population will respond to a disaster. Hazard and vulnerability are interrelated, although in the past hazard assessment has been focused in the hard sciences and vulnerability was perceived as more of a social science discipline. Table 2-5 presents an overview of the components of vulnerability and their relationship to demographic, political, hazard, and scientific factors.

Table 2-5: Components of Vulnerability and their Determinants

Components of Vulnerability	**Variables involved**	**Socio-economic and Technical Determinants**
Initial Well-being	Nutrition; physical & mental health; Morale/faith; Capacity for self-reliance	Class position; Gender; Ethnicity; Age; State and civil society
Livelihood resilience	Income opportunities; Livelihood type; Qualifications; Assets and savings	As above, plus: Shifts in power relations and effects on livelihood after hazard impact
Self Protection	Building quality; Hazard protection; Location of home and livelihood	As above, plus: Technical ability & knowledge of and availability of protective measures; Hazard-specific Type of protection, its cost and feasibility; Return period; Duration; Intensity; Magnitude
Societal Protection	As above, plus: Building regulations Technical interventions by higher levels	As above, plus: Level of scientific knowledge; Characteristics of technical practices Quality and robustness of insurance systems; Type of science and engineering used by state and dominant groups

Social Capital	Social cohesion; Rivalries; Number & strength of potentially conflicting groups	As above, plus: Type of state power; Capacity for civil society to develop and enable positive networks and interactions
Taken from Cannon, 2000		

Epidemiologic analysis during the event focuses on rapid assessment to prioritize needs and minimize morbidity and mortality. These assessments are methodologically simple and the quality of the data is highly dependent on available personnel and infrastructure. The goal of this assessment is to retain control over the disaster situation and provide framework to help at-risk persons avoid the disaster and affected persons recover from the disaster (Cuny, 1983). The competing objectives of time constraints and thoroughness limit the usefulness of the data beyond the immediate situation (Bradt, 2003). A minimal amount of information is obtained on site to guide the immediate recovery effort, but these data has limited utility in elucidating the risk factors in order to understand casual factors and prevent future morbidity.

The final component of disaster epidemiology is post-event assessment. Disaster mitigation is most effective when implemented before a disaster and post-disaster studies are effective tools in preventing future morbidity and mortality and developing appropriate preparedness guidelines. These studies typically involve more traditional epidemiologic methods such as cross-sectional, case-control, and cohort studies. The goal is to quantify risk factors for morbidity and mortality and develop evidence-based strategies for hazard and vulnerability reduction in future events. This is by nature a multi-disciplinary task and historically there has been a dearth of well-researched disaster assessments. The 1994 United Nations World Conference on Disaster Reduction concluded.

"Disaster prevention, mitigation and preparedness are better than disaster response in achieving the goals and objectives of the Decade. Disaster response alone is not sufficient, as it yields only temporary results at a very high cost. We have followed this limited approach for too long. . . . Prevention contributes to lasting improvement in safety and is essential to integrated disaster management."

Effective post-event surveillance allows for the assessment of human health impacts, the identification of preventable risk factors, the improvement of surveillance methodologies, and evaluation disaster preparedness, response, and recovery. These factors can only be appropriately addressed with thorough research taking in to account the complexities involved with studying disasters. While the causes of morbidity and mortality in some disasters are obvious, multiple studies are needed to tease out the more complex causal factors to effectively modify interventions.

2.4 Earthquake Epidemiology

Earthquake epidemiology has been defined as "the study of the distribution of death and injury in earthquakes and the causes of fatal or nonfatal injury" (Jones, 1994). The goal of earthquake epidemiology is to reduce loss of life and injury from future events. This is accomplished through improving disaster education, planning, casualty estimation, response, and relief efforts.

"Better epidemiologic knowledge of causes of death and types of injuries and illnesses caused by earthquakes is clearly essential for determining what relief supplies are

appropriate and what equipment and personnel are needed to respond effectively to such situations, as well as to improve preparedness and reduce vulnerability to the effects of future earthquakes" (Noji, 1997).

In order to develop successful interventions, the specific types and causes of injury and death in historical events must be examined. An important source of information is post-earthquake data collection. The experiences of victims and survivors are paramount in understanding causal mechanisms in earthquake morbidity. Despite the importance of post-event epidemiologic analysis, historically studies of earthquake injury were most often found in the engineering literature or were assessments made by health professionals that did not employ sound epidemiological methods (Jones, 1993).

It was not until the 1976 Guatemalan earthquake that epidemiologic methods were used in an earthquake injury assessment. The resulting article focused on the reduction of morbidity and mortality through changes in building practices (Glass, 1977). Early literature in the field of earthquake epidemiology was concentrated on structural collapse and the relationship between casualties and building response. This research was paramount in developing building materials and techniques and guiding building codes. Since then a body of literature has developed focusing on the seismic, structural, socio-cultural, and demographic characteristics associated with earthquake morbidity. However, the body of literature looking at earthquake casualties still pales in comparison to that focused on geological and building related seismic effects.

Table 2-6 provides an overview of the epidemiologic literature associated with earthquake morbidity and mortality. It is restricted to those studies dealing with the relationship between seismic, structural, demographic, socio-cultural aspects, and descriptive medical aspects of earthquake injury and death. This literature review does not include case studies of specific medical outcomes, such as the effectiveness of dialysis in victims of crush syndrome or treatment protocols for burn injuries sustained as a result of an earthquake. Specific mechanisms of injury are evaluated briefly in a subsequent section of the literature review. The literature review also does not include non-physical morbidity outcomes such as post-traumatic stress syndrome and other psychological outcomes that occur as a result of a catastrophe.

The table is restricted to those events that have been studied using epidemiologic methods. Because of this, only a small portion of the major earthquakes of the past 30 years are included. The table includes the location of the earthquake, the magnitude, the date and local time of occurrence, the number of officially reported injuries and deaths, and a brief description of the type of study and major variables evaluated. The number of injuries and deaths in earthquakes can differ drastically depending on the source of the report. The numbers reported in the table are the official estimates provided by the USGS or a local governmental emergency organization.

Table 2-6: Earthquake Casualty Studies Employing Epidemiologic Methods

	Location	Mg	Time	Date	Deaths	Injury	Studies-Type and factors evaluated
1	Guatemala	7.5		2/4/76	22,800	76,500	1) Village census
2	Bucharest	7.3	21:21	3/4/77	1,570		1) Review
3	Santa Barbara, Ca	5.7	15:55	8/13/78	0	85	1) Review
4	Imperial County, Ca	6.6	16:16	10/15/79	0	78	1) Review

5	Algeria	7.3	12:25	10/10/80	5,000	9,000	2) Review
6	Italy	6.8	15:43	11/23/80	3,000	7,750	1) 7 village morbidity and mortality survey
7	Coalinga, Ca	6.7	16:42	5/2/83	0	211	1) Review
8	Chile	7.8	19:47	3/3/85	180	2,575	1) Hospital Survey
9	Mexico City	8.1	11:00 7:18	9/19/85	7,700	30,000	1) Review 2 buildings 2) Review 3) Juareaz Hospital
10	San Salvador	5.5	11:50	10/10/86	1,000	10,000	1) Building cohort
11	Whittier Narrows, Ca	5.9	7:42	10/1/87	8	1,300	1) RDD survey demographic, structural, behavioral factors (n=690)
12	Armenia	6.9	11:41	12/7/88	25,000	31,000	1) Case-control study of rescue and medical care 2) Rapid survey 3 towns 3) Case-control hospitalized injuries, demographic, behavioral (n=189, n0=159) 4) Cohort ministry of health-seismic, structural, demographic 5) Cohort 12,000 hospitalized patients
13	Loma Prieta, Ca	7.1	17:04	10/17/89	62	3,757	1) RDD survey demographic, structural, behavioral factors n=656
14	Luzon, Philippines	7.7	16:28	7/16/90	1,620	3,000	1) Case-control study of injuries, observation of rescue

15	Costa Rica						1) Retrospective interviews of survivors and medical personnel
16	Erzincan, Turkey	6.9		3/13/1992	498	2,000	1) Data review, field surveys, and site inspections
17	Northridge, Ca	6.7	4:41	1/17/94	33	7,000	1) Medical records review, demographic, seismic, structural 2) Case-control fatal and hospitalized injuries, seismic, structural, demographic factors (33 deaths, 138 injuries, n0=1831 households) 3) RDD survey demographic, structural, behavioral (n=1,830) 4) Hospital survey before and after earthquake 5) Review of fatal and hospitalized injuries demographic, structural 6) GIS mapping fatal and hospitalized injuries
18	Kobe, Japan	7.2	5:46	1/17/95	6,300	42,100	1) Matched case-control, one city (n=1,104,n0=1,104) 2) Autopsy findings 3) Morbidity and mortality of hospitalized patients
19	Turkey	7.4	3:01	8/17/99	17,000	24,000	1) Community needs assessment 2) Household survey, demographic, building, seismic, behavioral factors

20	Athens		14:57	9/7/1999	143	16,000	1) Autopsy findings
21	Chi-Chi, Taiwan	7.3	1:47	9/21/99	2,350	8,720	1) Casualty data from govt. records and hospitals 2) Population-based cohort, demographic factors (1.2 million, 1,610 cases) 3) Community Needs, Morbidity and Mortality Survey 4) Mortality data, SMRs, building factors
22	Bam, Iran	6.8	5:30	12/26/03	30,000	30,000	1) Descriptive analysis, hospital records

1) (Glass, 1977)
2) (Pomonis, 1992)
3) (Aroni, 1985)
4) (Aroni, 1985)
5) (Pomonis, 1985)
6) (De Bruycker, 1983)
7) (Aroni, 1985)
8) (Earthquake Engineering Research Institute, 1986)
9) 1 (Pomonis, 1992) 2 (Durkin & Ohashi, 1989)
10) 1 (Shoaf, 1998) 2 (Goltz, 1992)
11) 1) (Noji, 1993) 2 (Armenian, 1990) 3 (Armenian, 1992)
4 (Armenian, 1997) 5 (Noji, 1990)
12) 1 (Shoaf, 1998) 2 (Durkin, 1993) 3 (Jones, 1993) 4 (Bourque, 1993) 5 (Pomonis, 1992)
13) (Roces, 1992)
14) (Pretto, 1994)
15) (Angus, 1997)
16) 1 (Mahue-Giangreco, 2001) 2 (Peek-Asa, 2003) 3 (Shoaf, 1998) 4 (McArthur, 2000)
5 (Peek-Asa, 1998) 6 (Peek-Asa, 2000)
17) 1 (Osaki, 2001) 2 (Aoki, 2004) 3 (Tanaka, 1999).
18) (Petal, 2004)
19) (Papadopoulos, 2004)
20) 1 (Liang, 2001) 2 (Chou, 2004) 3 (Chen, 2003) 4 (Chan, 2003)
21) (Naghi, 2003)

2.5 Methods of Earthquake Casualty Research

Earthquake epidemiology has in the past been primarily descriptive. Only a small percentage of studies have employed more quantitative epidemiologic methods. Most are either convenience samples or descriptive reports of first responders, medical personnel, or damage assessors. The early literature was entirely reviews of coroner or hospital records or descriptive studies of a convenient sample, such as a single village. These studies also tended to focus only on characteristics of construction leading to injury or death, giving an incomplete picture of earthquake casualty. In addition, there is significant variation between events and each event has unique characteristics and challenges increasing the difficulty in studying earthquake casualties.

2.5.1 Case-Control

Earthquake injury and death is typically a rare event and there is often a need to rapidly assess risk factors. For this reason the case-control study design lends itself to earthquake casualty studies. The overwhelming majority of analytic studies of earthquake morbidity and mortality have been case-control. In these studies, cases are typically those killed or hospitalized, and in smaller events, those seeking treatment in hospitals. Controls are selected from the population, often at a much later date. In matched case-control studies controls are typically selected from a similar geographic region as fatal and hospitalized cases are identified. Control selection is done through telephone, face-to-face household surveys, or mail in surveys. It can be difficult to obtain a random sample given the displacement that often occurs after a major disaster and the complexities associated with determining the population at risk. Coroners' reports and medical records allow cases to be identified and studies performed significantly after the event. However, the quality of these records can be questionable during a major disaster.

The issue of recall bias among both cases and controls has been shown to be less of an issue in epidemiologic studies of disasters. In most epidemiologic studies of disease, especially chronic disease, recollection of events fades over time. On the contrary, with significant life events, such as a natural disaster, memories remain consistent over time. In an article looking at survey research in disasters, the authors found that respondents are unlikely to forget the events occurring during a disaster and that for some the information becomes clearer after the event when they have had time to process (Shoaf, 2000).

Another common issue in epidemiologic studies is high refusal rates in control selection. This does not seem to be the case with disaster epidemiology. People tend to be willing to talk about their experiences during a disaster even if they did not experience a negative health outcome. In a survey of more than 400 respondents after the 1998 Armenian earthquake the refusal rate was less than one percent (Noji, 1990a). After the 1989 Loma Prieta earthquake the refusal rate in a case-control study conducted in Santa Cruz County was 7.5 percent (Jones, 1992). Low refusal rates common in disaster epidemiology make it likely that study groups are representative of the general population, thus reducing selection bias.

2.5.2 Cohort

Several studies have employed a cohort approach to studying the impact of earthquakes. The cohort approach was first used after the 1988 Armenian earthquake.

The study was a population-based cohort based on payroll data from Ministry of Health employees and their immediate families living in the earthquake region. This cohort was representative of the population, albeit with better access to healthcare. Employees were interviewed and asked about their earthquake experiences and geographic, structural, demographic factors were considered (Armenian, 1997). Another cohort study evaluated demographic risk factors in the 1999 Chi-Chi earthquake. Researchers designed a population-based cohort from a government maintained database. This allowed them to couple demographic information with health status information obtained from the National Health Insurance Program in order to evaluate the relationship between death and demographic factors, physical health, and SES (Chou, 2004).

The cohort approach allows follow-up on the long-term effects of the earthquake, limits the selection bias that occurs due to post-event displacement, and gives baseline estimates of the risk of injury and death in the population. There are significant difficulties and expense in determining and following an appropriate cohort in an earthquake, therefore, case-control studies will likely remain the standard in earthquake epidemiology.

2.5.3 Descriptive and Other Study Types

The majority of earthquake casualty studies are still descriptive. These are typically event reports of casualties associated with building collapse or descriptions of casualties that receive medical treatment at a particular institution. These studies tend to emphasize either the medical or structural factors of earthquake morbidity and mortality. Methods of descriptive studies include field data collection from hospitals or specific buildings, small convenient samples such as the occupants of a specific geographic area or building, and reports from experts in the field. If data is needed quickly or a relevant control group is not available, then descriptive studies may be the only option. This type of study is paramount in determining risk factors and developing hypotheses, but more analytic studies are necessary to determine whether these associations are real.

Autopsy reports and field hospital surveys are an important mechanism for determining causes of death and developing medical recommendations. Understanding the mechanisms involved in earthquake death helps to establish a critical time frame for rescue. An autopsy study of the 1999 Athens earthquake demonstrated that the majority of fatalities were not immediate and that deaths from asphyxia and hemorrhaging could have been prevented with more timely access to medical treatment (Papadopoulos, 2004). Field hospital surveys help in determining the types of medical personnel and equipment that needs to be available after an earthquake. After the 1999 Turkish earthquake, researchers found that the medical needs changed drastically in the week following the earthquake (Bar-Dayan, 2000).

2.5.4 Issues in Earthquake Epidemiology

There are a number of unique challenges associated with earthquake epidemiology. Earthquakes are unpredictable and cause significant disruption, both during and after an event, making earthquake epidemiology complex. Some issues include each event's unique nature, the difficulties of defining and classifying earthquake-related casualties, obtaining reliable data, identifying an appropriate control group, and doing sound multi-disciplinary research.

Each earthquake has a unique set of characteristics that influence morbidity and mortality. The seismic characteristics differ greatly. Even in events of the same magnitude the geologic substrate and topography of the local area can cause vastly different injuries. In addition, construction types differ greatly by regions of the world. Although reinforced concrete may be protective against injury and death in the United States, the addition of infill walls and sub-standard construction techniques may increase the hazard in developing countries (Godden, 1997; Petal, 2004). The same occupant response during an earthquake may be protective against injury in one event and be a risk factor in another event. Differences in population density, setting, infrastructure, and local emergency response can cause immensely different casualty patterns in similar seismic events. No universal set of guidelines can be developed for earthquakes, but by comparing and contrasting risk factors for morbidity and mortality overall risk can be minimized.

The extreme variation in the number and severity of earthquake injuries and deaths makes it difficult to develop a uniform definition of earthquake injury. In the event of a significant number of fatalities researchers are unlikely to evaluate minor injury and casualties not directly caused by the earthquake, such as heart attacks (Coulson, 1989). This makes comparisons between events extremely difficult. Injuries can be classified as a result of mechanism, type of injury, severity, or a number of other categories. The lack of a universal injury coding system can cause misclassification, which can potentially lead to bias.

Obtaining reliable data is extremely difficult in an earthquake situation. Official injury estimates are usually derived from quick surveys of major healthcare providers and typically do not include medical treatment rendered by aid groups, urgent care clinics, family physicians, friends and neighbors, and self. A significant number of injuries are treated outside of the health care system. Durkin (1991) estimated that as many 60 percent of injuries sustained in the 1989 Loma Prieta earthquake were treated in non-hospital settings. A comparison of official injury statistics with a population-based RDD survey after the Northridge earthquake lead researchers to hypothesize that the actual number of injuries sustained was two to three times official estimates (Shoaf, 1998).

Emergency room and hospital record reviews can result in an overestimate of earthquake casualties. Especially if the assumption is made that all people presenting for medical treatment post-earthquake are earthquake-related casualties. After the Northridge earthquake, estimates of earthquake-related hospitalized injuries and illnesses were approximately 1,500 cases, but after a thorough review of hospital admissions records, using a standardized case definition, it was found that only 138 of those were actually earthquake-related injuries (McArthur, 2000). This illustrates two issues; the need for a definition of what constitutes an earthquake-related injury and the unreliability of hospital-based estimates in determining earthquake casualties.

The reliability of medical records often becomes questionable during major disasters. In the event that medical records are kept, the information is likely to be sparse. It can be difficult to determine which injuries were earthquake related. In addition, key questions such as geographic location and actions at the time of earthquake are unlikely to be included as part of the medical record. It is also difficult to track cases after earthquakes as places of residence are destroyed and significant numbers migrate out of area. In a cohort study of 9017 people following the 1988 Armenian earthquake 927 had migrated out of area with no follow-up address (Armenian, 1997).

Case-control studies often have a difficult time obtaining an appropriate control group. Estimating the population in the area at the time of the earthquake can be complex. The proportion of people commuting in or out of an area can greatly affect the population at risk even when good census data is available. In many developing countries, quality census data may not be available and the demographics of the population may not be known. Significant migration out of an area often occurs after an earthquake. It is probable that those who leave were more likely to have suffered significant building damage, and it has been shown that building damage is a correlate of injury and death. This could bias results in case-control studies where data is collected post-event. Most studies of earthquake epidemiology are descriptive or utilize a convenience-based control group, because of issues associated with obtaining an appropriate control group. Analytic studies are necessary to test hypotheses and obtain exposure odds ratios for specific hazards.

Earthquake epidemiology is multidisciplinary in nature. Collaboration between medical personnel, epidemiologists, first responders, geologists, and structural engineers is necessary in order to understand the factors associated with earthquake casualties. Studies conducted by epidemiologists often fail to address engineering and architectural principles that would help in preventing future morbidity (Gordon, 1989). Similarly, structural engineers often focus entirely on building response without any regard for non-structural hazards, which are responsible for a majority of injuries in developed countries. Better epidemiologic knowledge is needed to determine individual-level factors that contribute to earthquake morbidity, but it is imperative that epidemiologic studies include variables important to medical personnel, architects, engineers, and government officials in order to have the necessary equipment, personnel, and supplies in earthquake prone regions.

2.6 Building Factors

In major earthquakes the most significant contributor to injury and death is partial or total building collapse (Coburn, 1992). The response of structures in seismic events is the most well studied aspect of earthquake research. Until the 1980's the earthquake engineering literature focused solely on the response of different structures to earthquakes and limited attempts were made to determine human casualty estimates from this information. This is in part because seismic building research is often driven by the insurance industry, whose major concern is economic losses resulting from building damage and collapse.

Determining the seismic risk of buildings requires data and assumptions about individual building performance in seismic events. A body of literature exists evaluating the relationship between individual building characteristics and casualties. This literature uses historical event data to attempt to predict casualty levels for individual buildings. These model parameters tend to include variables such as occupancy of the building as a function of time of day and season, occupancy of the building by function, casualty rates as a function of construction type, and search and rescue effectiveness (Pomonis, 1991). Based on building characteristics and physical factors such as the magnitude of the earthquake, geography, and soil type, predictions are made as to how a particular building will respond. Buildings can totally collapse, partially collapse, have major structural damage, have minor structural damage, or sustain only non-structural damage. Human casualties can be estimated with information about building damage and occupancy rates coupled with historical injury and death rates by building damage and type.

2.6.1 Construction Materials

Earthquake building studies show that construction type is a key characteristic in determining earthquake casualties. Some construction types are more prone to damage and given damage more prone to causing death or injury. The main determinant of vulnerability is type of construction of the main vertical-load bearing elements (Coburn, 1992). The MSK intensity scale divides buildings into four types based on their seismic vulnerability. Type A or weak masonry includes adobe, stone, and earthen construction and is highly vulnerable to seismic damage. Type A is most commonly found in the developing world or in older buildings in developed countries. Type B includes unreinforced brick, concrete block, and dressed stone masonry. Type C includes timber-framed structures and reinforced concrete framed structures, this type of construction responds far better in seismic events, and is common in residential construction in seismically active pars of the United States. Type D includes structures engineered for earthquake performance with reinforced frames, these are expensive to build and require considerable technical expertise (Medvedev, 1968). Not all structures of the same type will respond similarly during an earthquake. Factors such as quality of construction, roof type, age of building, height of building, and structural form also influence building response, in addition to construction type.

The primary cause of earthquake fatalities is collapse of poorly constructed or non-seismically sound buildings. It is estimated that as many as 75 percent of earthquake related fatalities this century can be attributed to these factors. If secondary hazards such as fires, tsunamis, and landslides are not considered, building collapse accounts for 90 percent of earthquake fatalities (Coburn, 1992). In the Chi-Chi earthquake the overwhelming majority of near fault mortality was people in mudbrick buildings. Especially in developing countries, the threat of building collapse is much greater as seismic retrofitting is expensive and therefore not a common practice. In addition, materials like adobe and concrete are extremely heavy and tend to kill or severely injure occupants upon collapse (Mehrain, 1991; Ceciliano, 1993).

The most seismically unsound buildings are those constructed of unreinforced masonry, such as adobe, rammed earth, rubble stone, and stone block. These types of buildings have historically been responsible for the greatest percentage of earthquake injuries and fatalities. Unreinforced masonry was a particular problem earlier this century before improvements in building technology and building codes were implemented. In developing countries, much of the residential construction is still unreinforced masonry buildings. In the 1976 Guatemala earthquake, virtually all deaths were related to the collapse of adobe structures (Glass, 1977). In the 1985 Chilean earthquake, over 54 percent of persons killed were in adobe structures at the time of the earthquake and 33 were in structures made of brick (Ortiz, 1986). In the 1998 Armenian earthquake, 100 percent of unreinforced masonry structures in an area close to the epicenter collapsed during the earthquake. In the 1999 Chi-Chi earthquake, mud-brick houses accounted for 50 percent of fatalities even though they account for only 4 percent of the construction (Liang, 2005). Although new building codes in most developed countries prevent unreinforced masonry construction in seismic areas, many older unretrofitted buildings remain. Unreinforced masonry construction is still a significant issue in countries where finances do not allow for the use of sophisticated building materials in residential construction.

Reinforced concrete is a sophisticated construction technique that can greatly limit the probability of building collapse, provided it is done correctly. Several failures of reinforced concrete buildings including Nicaragua 1972, Mexico City 1985, and Armenia 1988 have demonstrated the danger of improperly constructed or inspected reinforced concrete buildings (Godden, 1997; Bertero, 1989; Wyllie, 1989). Debris from masonry, brick, and adobe building can easily be removed by rescuers, whereas rescue from collapsed reinforced concrete buildings requires heavy machinery, which may or may not be available in a timely manner in a disaster situation (Noji, 1989).

Pomonis (1992) reviewed earthquake deaths in a number of major urban earthquakes over the past 30 years. The study found that the failure of concrete buildings was responsible for an overwhelming number of earthquake fatalities. The results are shown in Table 2-7 below.

Table 2-7: Concrete Building Failures Resulting in High Fatalities

Location	Year	Deaths	% due to concrete failure
Bucharest, Romania	1977	1,570	70
El Asnam, Algeria	1980	3,500	>40
Mexico City	1985	7,700	>90
San Salvador	1986	1,000	>35
Armenia	1988	25,000	>30
Luzon, Philippines	1990	1,550	>75
Pomonis, 1992			

The failure of a concrete building can result in a large number of casualties. In the 1980 Algerian earthquake, 500 of the 3,500 deaths resulted from one single collapsed market and residential structure (Pomonis, 1992). The high population density, collapse characteristics, and long rescue time of concrete structures makes them particularly lethal in the event of collapse. In the 1999 Chi-Chi earthquake, 411 of the deaths are attributable to the collapse of high-rise reinforced concrete residential structures, including almost 100 deaths in Taipei, which is located over 150 kilometers away from the epicenter.

Reinforced concrete buildings are often constructed with unreinforced infill walls, which are hazardous in the event of an earthquake. They are often weak and not designed as part of the original structure. This can create regions of high stress causing local failure or they can attract load because of their stiffness and then fail in such a way that can cause serious building damage and injury (Coburn, 1992). In the 1999 earthquake in Turkey, reinforced concrete structures with unreinforced infill walls were responsible for an overwhelming number of the casualties (Petal, 2004). In order to avoid casualties from infill walls, they should either be incorporated into the structure or completely separate so that they do not put additional strain on the frame (Coburn, 1992).

Globally, protection from seismically related structural failure is highly variable. Those countries with technological, financial, and industrial resources, such as the United States and Japan have established building codes designed to resist minor earthquakes, resist moderate earthquakes with minimal structural damage, and to resist major earthquakes without catastrophic failure of the building framework (Applied Technology Council, 1985). In order to develop building guidelines a survey of California buildings was done by the Applied Technology Council. The result of this study was the ATC-13 classification system, which is the standard for vulnerability to seismic failure based on building type (Applied Technology Council, 1985).

2.6.2 Building Damage

There is a direct relationship between building damage and casualty rates, especially fatalities. The more damage an individual building sustains the greater the likelihood that occupants were injured or killed during the earthquake. Mortality among those living in buildings that are completely destroyed is significantly greater. In the case of the Kobe earthquake, complete collapse was such an overwhelming factor that epidemiologic studies were stratified on level of structural collapse (Osaki, 2001). In the Northridge earthquake, 15 of the 17 apartment related deaths were in an apartment complex that required demolition (Peek Asa, 1998). This pattern is also evident in the Chi-Chi earthquake and the relationship between building damage and morbidity and mortality will be explored in detail.

The degree of damage is not the only factor influencing the relationship. The type of damage, specifically type of collapse, is a strong driver in the number of casualties. A detailed study of building damage and fatalities done in Nishinomiya City after the Kobe earthquake found that 85 percent of fatalities could be traced to completely collapsed building with no survival space (Hengjian, 2003). Certain construction classes such as unreinforced masonry and masonry are much more likely to collapse without survival space contributing to the large numbers of casualties attributable to these construction classes. In contrast, many of the modern engineered structures are designed to maximize survival space in the event of collapse.

2.6.3 Quality and Age of Construction

The quality of construction is a major factor in building collapse, however, it is difficult to quantify and has not been effectively studied. It has been demonstrated that poorly constructed reinforced concrete can create a major hazard in a seismic event (Godden, 1997; Bertero, 1989; Wyllie, 1989). It has also been shown that structures built with less sophisticated techniques and cheaper materials are more prone to collapse. Morbidity and mortality is particularly high when these poorly constructed buildings are made of heavy materials such as adobe or mudbrick (Liang, 2005; Glass, 1977; Noji, Armenian, 1993; Pomonis, 1990).

Year of construction has also been related to morbidity and mortality in earthquakes. The first epidemiologic study of earthquake injury demonstrated age of construction to be a significant risk factor (Glass, 1977). Typically, the older the building the greater the risk is of failure and subsequent injury or death. This can be related to technological advancements in building materials as well as the introduction of seismic building codes. In the 1994 Northridge earthquake it was found that those in a building built prior to 1960 were 4.6 times more likely to be injured than those in buildings built after 1975 (Mahue-Giangreco, 2001). Improvements in building codes reduced the likelihood of structural collapse. The opposite trend was found in the 1999 earthquake in Turkey. More injuries and deaths occurred in those buildings constructed after 1976 when seismic building codes were enacted (Petal, 2004). In this case the seismic characteristics of the earthquake exceeded those designed for in the building codes. It is possible that the heavier construction materials may have lead to more injuries and fatalities.

It has been demonstrated that earthquake resistant construction can be effective in preventing morbidity and mortality, but in the event of structural failure seismically resistant construction can do more harm than good. Extricating victims from seismically reinforced masonry on concrete buildings requires heavy machinery and specialized skills. For this reason it is important that models be run to ensure that building codes are able to withstand the largest event likely to affect an area and that the technical expertise matches the technology when seismically sound buildings are constructed.

2.6.4 Height of Building

There is evidence that the height of a building is a risk factor for injury and death in earthquakes. As building height increases, risk of injury also increases. This association may be attributable to the fact that escape from an upper floor is unlikely. Coburn, Spence, and Pomonis hypothesize that as many as 70 percent of building occupants are likely to be trapped inside in the event of a high rise collapse (1992). In addition, people on higher floors may be more likely to be injured by building contents and are less likely to receive medical treatment in a timely manner (Armenian, 1992).

In the 1990 Luzon earthquake persons inside buildings with seven or more floors were 34.7 (95% CI=8.1- 306.9) times more likely to be injured (Roces, 1992). In the

Northridge earthquake those living in multi-story buildings were twice as likely to have been injured as those living in single-family dwellings (Shoaf, 1998). Studies from the Armenian earthquake showed a similar trend with risk of injury increasing as building height increased (Armenian, 1992). In a multivariate model adjusted for age, gender, and location, the odds of death were 56.3 times greater for those in buildings greater than 9 stories than for those in single story buildings (Armenian1997). A confounder of this relationship may be that a multi-story building collapse will cause a significant number of injuries and deaths, whereas collapse of a single family dwelling will result in only a few casualties. It is common, especially in developed countries, for the collapse of a few structures to account for the majority of fatalities. There is evidence that multi-story buildings, especially soft story buildings, are prone to structural weakness and collapse (Coburn, 1992).

2.6.5 Damage due to other Human Engineered Non-building Structures

Damage due to transportation systems such as bridges, railways, and roadways can be a major factor in earthquake morbidity and mortality. The most poignant example of this is the 1989 Loma Prieta earthquake, in which 68 percent of the total deaths resulted from the collapse of a portion of the 880 freeway. An additional death was caused by the collapse of a part of the upper deck of the Bay Bridge onto a driver (Eberhart-Phillips, 1994).

There are a number of difficulties associated with studying the effect of buildings on earthquake morbidity and mortality. The inconsistencies among building type, material, and quality make it nearly impossible to develop uniform recommendations.

The most appropriate response to an earthquake varies by the size of the earthquake, geographic location, and building characteristics. If the likelihood of building collapse is minimal, the most appropriate course of action is to duck and cover, because movement during the earthquake is likely to result in injury. On the contrary, if the building is likely to collapse leaving the building at the cost of injury may be the only way to avoid fatality. Unfortunately, it is nearly impossible to assess the probability an individual building collapse while an earthquake is occurring and take appropriate action in a timely manner. Although many structures may be at risk of partial or total collapse, the vast majority of casualties tend to be focused in a relatively small number of structures (Coburn, 1992).

2.6.6 Entrapment

Entrapment and the ability to be rapidly extricated is a significant factor in earthquake morbidity and mortality. In total building collapses in the 1995 Kobe earthquake, 70 percent of people were trapped by the contents of the building and 28 percent were physically trapped, due to confinement of a body part (Murakami, 2004). Entrapment has a strong relationship with earthquake injury and death. In the Loma Prieta earthquake, those slowed or prevented from exiting a building because of debris had a 6.0 (95% CI = 1.34-26.91) times greater risk of being injured. In a post earthquake survey of a rural area in Armenia, death rates were 67 times higher and injury rates 11 times higher among those trapped (Petal, 2004).

The ability to survive while entrapped is a function of a number of different variables including health condition, building materials, weather, and air supply. The construction material and physics of the collapse determine the number and size of void spaces in a collapse. The larger these spaces are the greater the likelihood that trapped victims will have enough air supply to survive until rescue. The majority of entrapment deaths are due to the aspiration of debris, dust, soil, blood, and gastric contents and injuries obstructing the airway. In the 1999 Chi-Chi earthquake, asphyxia was the major cause of 34 percent of deaths (Liao, 2004). In the 1999 Athens earthquake, 31 of 111 autopsied deaths were as a result of asphyxia. Most are preventable with earlier access to medical care. Deaths from asphyxiation are particularly common in the collapse of unreinforced masonry, where compact piles with minimal void spaces leave little chance for long-term occupant survival (Glass, 1977; Pomonis, 1990; Noji, 1993). Other causes of entrapment death that could potential benefit from early medical intervention include bleeding, burns, and cardiovascular events such as myocardial infarction. In the 1980 Italian earthquake, it was estimated that between 25 and 50 percent of deaths would have been prevented with immediate medical care (Safar, 1987).

It is difficult to determine at what point a trapped victim died, but the evidence shows that the sooner extrication occurs the greater the likelihood of survival and less serious injury. A case-control study was conducted during the 1988 Armenian earthquake where case subjects were hospitalized and control sustained only minor injuries. The odds of cases being trapped for more than 1 hour was 2.79 (95% CI = 1.52-5.13) times that of controls and the odds of cases being trapped greater than 6 hours was 3.88 (95% CI = 1.69-9.10) times that of controls (Noji, 1993). These data indicates that the seriousness of the injury increases with entrapment time. Similarly, the probability of survival decreases as duration of entrapment increases (Roces, 1992; Sheng, 1987; De Bruycker, 1985). Evidence from earthquakes in Turkey and China indicated that after 2 to 6 hours, half of those buried are still alive (De Bruycker, 1985). In one area in the 1988 Armenian earthquake, 89 percent of those extricated alive were rescued in the first 24 hours (Noji, 1990). In the 1980 earthquake in Italy 93 percent of those rescued in the first day survived (De Bruycker, 1985). The first 24 hours after an earthquake is referred to as the Golden Day when the vast majority of live rescues are accomplished. The probability of survival diminishes rapidly after the first day. In the 1990 Philippines earthquake, 99 percent of the 235 survivors pulled from the rubble were rescued within the first 48 hours (Roces, 1992). This demonstrates the importance of having local rescue teams able to respond immediately after the earthquake. International assistance teams arriving days after the event are unlikely to have a significant impact of reducing mortality in a large earthquake. The ability to rapidly model the spatial pattern of casualties immediately post-event should allow for the better prioritization of search and rescue resources and the reduction of entrapment times.

Rescue teams are often composed of uninjured survivors not professional rescuers. In the 1976 Tangshan China earthquake, 200,000 to 300,000 people crawled out of the debris on their own and began rescuing others (Chen, 1988). These civilian rescuers are credited with saving 80 percent of those victims buried under debris. In urban areas especially, there is a small number of professional first responders and medical personnel for a large number of residents. This underscores the importance of civilian disaster training programs, as untrained personnel are often responsible for a majority of rescues. Civilian rescue efforts are far less effective in the collapse of reinforced concrete buildings. The need for heavy equipment and specialized rescue teams minimizes the impact untrained rescuers can have in this type of collapse.

Another factor affecting survival in entrapment is the ability to access medical care in a timely manner. In an autopsy study of the 1999 Athens earthquake, physicians found that two-thirds of the patients sustained non-fatal injuries during the earthquake and that entrapment and inability to access medical care was a major factor in the fatalities (Papadopoulos, 2004). High demand and damage to infrastructure can limit access to medical care. During the 1999 earthquake in Taiwan, it was determined that modular teams with search and rescue and medical capabilities would be effective in minimizing deaths provided they were appropriately allocated (Liang, 2001).

2.7 Individual Factors

Geographic and structural factors are significantly more important than demographic factors. The overwhelming majority of earthquake casualties occur because of structural failure. In the Chi-Chi earthquake 90 percent of fatalities can be directly attributed to building collapse. Although the literature has shown some association with individual factors they are often a result of confounding due to building and geographic factors rather than a casual association. Individual level factors are often not consistent between earthquakes and a characteristic that increases risk in one earthquake may be protective in another.

2.7.1 Location

There is evidence that location during an earthquake can be a predictor of injury or death. This can be a difficult concept to extrapolate between events as location and patterns of injury are likely to differ between earthquakes that occur during the day and during the night, as well as in rural and urban settings. In the majority of earthquakes in rural areas, those outside when the shaking begins are far less likely to experience injury or death (Noji, 1990; Armenian, 1992; Jones, 2003). In the 1992 Turkey earthquake, 87 percent of fatalities were inside at the time of the earthquake (Angus, 1997). In a cohort study of the 1988 Armenian earthquake the risk of death was 10.1 (95% CI=6.5-15.9) times greater for those inside when the shaking began compared to those outside (Armenian, 1997). With the exception of geographical location, being inside at the time the shaking began was the strongest predictor of death in the Armenian earthquake, which can be attributed to structural collapse.

However, not all earthquakes have shown being inside as a risk factor for injury or death. In the 1990 Luzon, Philippines earthquake, the distribution of the location was similar for cases and controls and being inside was not a strong risk factor (Roces, 1992). In the 1970 Peruvian earthquake, those who escaped into wide streets were protected from injury, but in the mountainous regions those who escaped into the narrow streets were more likely to experience injury and death (Clapperton, 1972). A thorough review of location during a daytime large urban earthquake has not been done, and hazards such as overhanging wires, multi-story buildings, narrow streets, and collapsing facades may increase the risk for those outside during an earthquake.

Occupants' location within a building also seems to be a predictor for injury. Occupants on upper floors in multistory buildings have an increased risk of injury. In a case-control study of the 1988 Armenian earthquake, it was found that occupants on the second to forth floor were 3.84 times more likely to be injured than those on the ground floor and occupants on the fifth floor or higher were 11.20 times more likely to be injured (Armenian, 1992). This result was confirmed in a cohort study, where risk of death was twice as great for those on upper floors compared to persons on the ground floor (Armenian, 1997). In the 1990 Luzon earthquake, persons on the middle levels of multistory buildings were 2.3 (95% CI=1.3-4.2) times as likely to be injured as those at the top or bottom levels (Roces, 1992). Similar results were found in the 1980 earthquake in Italy and the 1985 Chilean earthquake, where being on the ground floor was found to be protective for injury and death (De Bruycker, 1985; Aroni, 1985). Analogous to the association with building height on the structural side this relationship may be confounded by the fact a multi-story building collapse will cause a significant number of injuries and deaths.

2.7.2 Behavior

The relationship between behavior and injury or death during an earthquake is important in developing preparedness messages. It is a difficult concept to study as information cannot be gathered from those killed in an earthquake and the appropriate behavioral response varies greatly by magnitude, location, and building type. Traditional recommendations include the duck, cover, and hold, taking refuge under a doorway, or exiting the building. There is some thought that exiting may be the appropriate course of action if there is the potential for building collapse, whereas staying still and employing duck, cover, and hold methods may be the best course of action when building collapse is unlikely. However, these recommendations may be overly simplistic as the best course of action is highly variable depending on seismic and building characteristics.

Exiting or attempting to exit the building is a factor often evaluated in earthquake injury studies. In the event of structural collapse, exiting the building seems to be the best way to avoid death even if injuries are sustained. In a study of the 1988 Armenian earthquake it was found that those who stayed in the building instead of exiting after the first shock had a 4.4 (CI 2.24-8.71) times greater chance of being hospitalized with an injury (Armenian, 1992). Similar results were found in the coastal regions in the 1970 earthquake in Peru, where those who rushed out of the building into the wide streets had a better chance of survival than those who remained inside and were trapped in collapsed houses (Clapperton, 1972).

However, the opposite was true in the Peruvian mountains where the rates of injury and death were higher among those who tried to escape. Those running into the narrow streets were buried by rubble when walls collapsed due to the heavy roofs common in the area (Clapperton, 1972). This same pattern occurred in the 1976 Friuli, Italy earthquake. Many in the Venzone parish were injured or killed by falling masonry when they attempted to exit buildings. The very young and old and those unable to exit had better probabilities of survival in this situation (Hogg, 1980).

In studies of California earthquakes where structural collapse is rare, attempting to exit the building seems to be a risk factor for injury. In a study of occupant behavior in one office building in the 1979 Imperial Valley earthquake, about one half of the injuries were caused by people attempting to exit and bumping themselves on objects or doorways. The authors concluded that attempting to evacuate unreinforced masonry buildings during the earthquake increased injury rates by a factor of three (Aroni, 1985).

In a study of 1,715 people in the Northridge earthquake, those who attempted to move had an injury rate of 10.4 percent whereas those who stayed in place had an injury rate of 6.1 percent (Shoaf, 1998). In addition, the strict seismic building codes in California do not apply to decorative elements. Numerous earthquake deaths in California have resulted from being hit by or crushed by unsecured balconies, bricks, and ornamental parapets. The inconsistencies between California and Armenia are “not necessarily contradictory because exiting from a poorly-built collapsing structure may protect against death while attempts to exit buildings that do not collapse may increase risk for injury” (Peek-Asa, 2001).

A difficulty in studying occupant response is the lack of independence between ability to exit and injury and death. Those injured or killed immediately would be unable to exit and those injured or killed while exiting may be misclassified into the remained inside category. Armenian (1992) acknowledges “it’s possible that many of the cases were unable to run out of the building because of their injury”. In addition, the condition of the building, both in terms of structural and non-structural hazards, may prevent people who otherwise would have exited from getting outside.

The relevant question is whether in a given earthquake exiting is relatively safer that remaining inside? This is highly dependent on the magnitude of earthquake, building characteristics, location within a building, and condition of the area immediately outside the building. One uniform set of recommendations cannot be developed for every earthquake, but rather similar earthquakes must be reviewed and casualty models developed to help guide recommendations. Occupant response is one of the elements that can be controlled to some degree by disaster preparedness education. For this reason it is important that more research, especially modeling, is done to determine the relationship between death and injury and behavior.

2.7.3 Demographic Characteristics

The vast majority of earthquake injury studies evaluate the relationship between demographic characteristics and earthquake morbidity and mortality. The variables that have shown an association are age, physical disability, and gender. Other demographic variables that have been evaluated include race, socioeconomic status (SES), and mental disability. However, these associations are likely confounded by structural and seismic factors. The increased fatality rate for the elderly and disabled can often be attributed to the fact they often live in older or sub-standard housing.

When structural factors are not accounted for age has been shown as a predictor of earthquake morbidity and mortality. In adult populations the risk of death and injury is often found to increase with age. A study of the Chi-Chi earthquake found a relationship with increasing age. Using 16-25 as a reference group, the adjusted risk of death was 1.3 times greater for 26-35, 1.6 times greater for 36-45, 2.1 times greater for 46-55, 3.5 times greater for 56-65, 5.5 times greater for 66-75, and 8.7 times greater for ages 75 and older (Chou, 2004). However, this study did not take structural factors into account and it is likely, as it was found in the Kobe earthquake in Japan, the elderly are more likely to live in older or less seismically sound buildings and that the association is actually caused by the difference in construction type.

In the Northridge earthquake, those over 59 had a 2.7 times greater risk that those aged 30-39. When the analysis was adjusted for other seismic and structural factors the strength of the relationship increased to a 6.06 (95% CI=1.64-22.4) times greater risk for those over 59. (Mahue-Giangreco, 2001). Similar associations between age and risk have been recorded in the Guatemala, Coalinga, and Kobe earthquakes (Glass, 1977; Aroni, 1985; Miyano, 1996).

The elderly may be more at risk for earthquakes death because they lack the agility to leave the building or avoid falling objects. They may be able to withstand less physical strain, so in the event of entrapment or delayed rescue they may be unable to survive. Those living alone may not have assistance in evacuation or rescue. There is evidence that survival rates may differ among elderly populations and that physical disability may be a more important predictor than age alone (Osaki, 2001). This association is likely confounded by structural factors.

An increased risk of injury and death has also been repeatedly shown among young children. Children lack in physical strength and may be less able to evacuate. They may also be unaware of how to appropriately respond to an earthquake. In addition, it is likely that they lack the physical capabilities to survive for prolonged periods of time if trapped. In the 1999 earthquake in Taiwan, children between 0-15 were 1.5 times more likely to be killed than those 16-25 (Chou, 2004).

Several studies have shown gender to be a risk factor for injury or death, but this association is not consistent. Fifty-eight percent of victims were female in the 2003 Bam earthquake in Iran (Naghi, 2005). A statistically significant difference was found in the

Chi-Chi earthquake where women had a 1.2 greater risk of injury than men (Chou, 2004). Females had a 2.4 times the risk of injury, in the Northridge earthquake, and an elevated risk of injury and death in the 1976 Guatemala earthquake (Peek-Asa, 2003; Glass, 1977). Reasons for this could include the social and cultural role of women. Women are more likely to be inside and may try and attempt to care for children and family members instead of themselves. Additionally, women are more likely to be in the home rather than in industrial or commercial buildings, which have a greater likelihood of having been seismically retrofitted.

Socioeconomic status is another demographic factor that has been periodically evaluated in the epidemiological literature. With lower SES and less money for quality construction and seismic retrofitting, homes tend to be less able to withstand earthquakes. It has already been demonstrated that level of building damage is a strong predictor for earthquake morbidity and mortality. In the Chi-Chi earthquake the risk of earthquake death increased as annual income decreased (Chou, 2004).

Determining individual-level variables that have consistent correlation with earthquake morbidity and mortality is a difficult task. The unique characteristics of the seismic event and the social and cultural characteristics of the area where the earthquake occurs can have a great effect on death and injury outcomes. Often events produce contradictory data. More research is needed to further understand the individual-level factors. Even with more research it is likely that the factors will vary by geographic area and there exists no set of universally applicable guidelines for minimizing earthquake losses.

2.8 Medical Aspects of Earthquake Casualties

2.8.1 Rates of Death and Injury

Estimating overall rates of earthquake injury and death is an exceedingly difficult task. A reason for this is enormous variation in the way casualty data is classified and reported. There is much to be gained by comparing injury rates between events. Unfortunately, the data are often not easily comparable and there is no one framework for classifying earthquake injury. This incomparability highlights the need for a universal injury classification system, but even that may not solve the problems with associated with inter-earthquake comparisons.

In order to compare relative risk a population at risk must first be determined. If the area selected is small and close to the epicenter the injury and death rates will be significantly higher than if a larger region is selected. If rates are given per unit of population, the population density of the affected area will have a profound effect on casualty rate estimates. The selection of an appropriate denominator can be complicated.

The quality of the data is another issue in mass-casualty events. As the number of casualties increase the estimates become more unreliable. It is nearly impossible for officials to identify and survey all healthcare providers post-earthquake. In events with a large number of injuries rarely do records exist for all patients seen in hospitals, clinics, and temporary medical facilities. In addition, official figures may be exaggerated or understated for political purposes.

Very few earthquakes have accurate population-based estimate of fatality and injury rates. Rough estimates exist for the 1988 Armenian earthquake as a result of cohort study that was conducted post-event and for the Northridge earthquake as all aspects were studied extensively. Estimated fatality rates range from .0037 per 1,000 population in the Northridge earthquake to nearly 500 per 1,000 population in the Armenian earthquake (Petal, 2004). Injury rates per 1,000 population range from .0193 in the Northridge earthquake to 641 in the Armenian earthquake (Petal, 2004). Rate estimates are often derived from small samples. The accuracy of these estimates is highly dependent on the appropriateness of the sample. A fatality rate of 2.52 per 1,000 and injury rate of 7.03 per 1,000 was derived for the 1990 Philippines earthquake using rough estimates by medical personnel (Roces, 1992). In the 1985 Chilean earthquake, researchers estimated death rates by region and they ranged from .003 to .052 per 1,000 with an average of .025 with a total affected population of 7 million people (Earthquake Engineering Research Institute, 1986). Injury rates followed a similar geographic pattern with rates ranging from .083 to .766, with an average of .365 over the same population. Despite the issues associated with comparing injury and fatality rates between earthquakes it is obvious that the casualty levels are significantly higher in countries with less economic resources.

Additionally, the severity of injuries that get reported varies by the magnitude of the event and the number of casualties. In mass-casualty earthquakes, minor injuries such as strains, sprains, lacerations, and even fractures are often not seen in medical facilities, because the number of more serious injuries limits access to medical care. USGS injury estimates for the Northridge earthquake are over 7,000 people, but a review of hospital data found that only 150 of those injuries required any hospitalization (Mahue-Giangreco, 2001). In larger events, such as the Chi-Chi earthquake the 11,000 reported injuries included only those that were seen in the medical system. Most likely there were a significant number of sub-clinical injuries that would have been counted in official estimates in less severe earthquakes like Northridge.

2.8.2 Injury to Death Ratio

An alternative method of comparing the severity of earthquakes is to look at the ratio of injuries to fatalities. It is expected that in less severe earthquakes the number of injuries for each death will be significantly higher. This comparison takes into account the fact that less severe injuries are likely be counted in less destructive events. In 1985 Alexander reviewed a number of major historical earthquakes and found that the ratio of injured to dead was typically 3 to 1 for earthquakes with magnitudes of 6.5 and above (Alexander, 1985). However, these estimates can vary greatly dependent on the severities of injuries included. Typically, in larger earthquakes only injuries treated by physicians will be recorded, but this is not universal. A follow-up study of injury to death rates conducted by Alexander in the mid-1990's found significant variation in injury to death rates, but with some events still close to the 3 to 1 ratio (Alexander, 1996).

Historically, developing countries had higher death to injury ratios, because of sub-standard building practices. This is no longer consistent as illustrated by the event data shown in Table 2-8. The variation in these ratios can be explained in part by the definition of injury and the sampling methods. Ratios approaching 3 to 1 can be expected in mass-casualty events in developing countries when only hospitalized injuries are evaluated. In developed countries, less severe earthquakes, or when minor injuries are also evaluated the ratio can be expected to increase significantly. The injury to death ratio can be an effective method for comparing severity between different regions in the same earthquake, but the utility of inter-earthquake comparison is limited unless the sampling methods are known.

Table 2-8: Injury to Death Ratios for Recent Earthquakes

Injury to Death Ratio				
Year	Earthquake	Injury to Death Ratio	Notes	
1985	Chile	14:1		1
1988	Armenia	23:1	Trapped victims	2
1989	Loma Prieta	57:1		3
1994	Northridge	4.2:1		4
1995	Kobe	6.8:1		5

1 Aroni, 1985; 2 Noji, 1990; 3 Durkin, 1991; 4 Borque, 1997; 5 Osaki, 2001

2.8.3 Injury Severity Scores

A standardized injury classification scheme is necessary in order to effectively quantify casualties and compare injuries between events. Classification systems have been used in trauma research order to effectively allocate resources, evaluate quality of care, and predict outcomes. A classification system has not been widely adopted in earthquake epidemiology and instead injuries are characterized descriptively by type or anatomic location. Noji proposed using a numerical methodology, such as a trauma score, derived from a standardized methodology. This would allow quick communication of medical information to facilitate effective triage and treatment (Noji, 1989).

The use of a standardized classification scheme would aid in planning, triage, the management of injuries, and tracking patients' conditions in extrication, transportation, and throughout medical treatment. These results could be used to test research hypotheses and in post-earthquake evaluations of medical and search and rescue efficacy (Noji, 1989). A standardized score would facilitate research into injuries resulting from structural collapse, entrapment, and rescue effectiveness.

Most injury classification schemes are based anatomically and physiologically. Anatomical classification relies of parts of the body affected and the amount of tissue and structural damage done to those body parts. Physiologic classification relies instead on the body's response to the injury. In mass-casualty situations, the physiologic classification system are far more useful, as non-medically trained personnel are often responsible for triaging. The trauma score uses seven circulatory, respiratory, and neurological parameters. These are respiration rate, respiratory expansion, systolic blood pressure, capillary refill, eye opening, verbal response, and motor response for field triage (Noji, 1989). A simpler system, based on the trauma score, developed for community responders in mass-casualty situations is RPM or respiration, perfusion, mental status. All ambulatory patients are categorized minor, those without respiration are categorized as dead, those with abnormal respiration, capillary refill of greater than 2 seconds, or abnormal mental status are categorized as immediate, and the remaining patients are categorized as delayed. This type of system has shown to be extremely effective at maximizing survival in mass casualties, but in order for this type of system to be applicable in an earthquake situation it must be universally understood by first responders.

Anatomical scales such as the Abbreviated Injury Scale (AIS) and its derivative injury severity scoring (ISS) have limited utility in the field, but can be used in retrospective medical record reviews. The AIS scale is a numerical scale between 1 and

6 used to rank injury severity, where 1 is minor, 2 is moderate, 3 is serious, 4 is severe, 5 is critical, and 6 is unsurvivable (Copes, 1989). The ISS is an overall score for patients with multiple injuries. It is assigned by first providing an AIS score and one of 6 regions of the body: head, face, chest, abdomen, and extremities, for each injury. The highest AIS score from the three most severely injured regions are squared and added together. The ISS score can have a value from 0 to 75 however if an injury is assigned an AIS of 6 the ISS score is automatically assigned to 75. This system is not a useful triage tool, but may be helpful in post-earthquake research.

The UCLA Center for Public Health and Disasters proposed a classification system for earthquake related injury. This system, shown in Table 2-9, incorporates AIS and ISS as well as the simpler physiologic scales commonly used in triage. No scale has been universally adopted in disaster situations despite the fact that the use of a universal injury severity scale would be an invaluable tool in earthquake epidemiology.

Table 2-9: Standardized Injury Classification Scheme

	Description	AIS	ISS
1) Lethal	The injuries are non-survivable even with immediate medical attention. Severe crushing injury and decapitation are examples.	At least one level 6	76
2) Severe	The injuries pose a serious threat to the individuals' life and require immediate medical attention.	At least one level 5, severe injury, or at least three regions with level 3 or 4 injuries	25 - 75
3) Moderate	Injuries are survivable, but may require medical attention. Without medical attention the injuries could become severe.	No more than two injuries with severity above 3 or 4	13 – 24

4) Mild	Injuries pose no serious threat to life if complications are prevented (such as infection of wounds)	No injuries above level 2	0-12
As taken from Shoaf, 2000			

2.9 Earthquake Fatalities

2.9.1 Medical Aspects of Earthquake Fatalities

The causes of death in earthquakes can be difficult to ascertain for a large number of casualties. Multiple trauma, head injuries, asphyxia, chest injuries, burns, and cardiovascular deaths stand out in the literature. The majority of fatalities are sustained from building collapse so multiple crush injuries are frequently reported. In the 1995 Kobe earthquake, the highest mortality rate among hospitalized patients was, 13.4 percent, patients with crush syndrome. The overall mortality rate was 5.5 percent with the leading causes of death being abdominal injury, head injury, and thoracic injury (Tanaka, 1999). Similar patterns appeared in an autopsy study of the 1999 Athens earthquake where multiple blunt trauma predominated with the most common fatal injuries being to the head, thorax, and abdomen (Papadopoulos, 2004). Nearly 30 percent of deaths in trauma patients were due to asphyxia caused either by compression injuries of the chest or airway or the inhalation of debris, soil, blood, or gastric contents (Papadopoulos, 2004). In the 1994 Northridge earthquake 22 of the 33 fatalities studied were due to a combination of asphyxia and compression during collapse (Peek-Asa, 1998). The parts of the body most affected in fatal injuries were the head (49 %), chest

(43%), external (24%), and abdomen (21%) (Peek-Asa, 1998) [1]. A study of the Chi-Chi earthquake found asphyxiation to be the number one cause of death accounting for 34.2 percent (Liao, 2005). Thirty percent of deaths were attributable to collapse related head injury, and traumatic complication to injuries of the truck or extremities, chest injury, crushing injury, and skull, spinal, or limb fracture made up the majority of the remaining deaths (Liang, 2001; Chan, 2003). These data indicates that some fatalities may be prevented if rescue is immediate and asphyxia does not occur and that covering the head to prevent blunt trauma is an important recommendation in decreasing fatalities.

There is also evidence of increased incidence of non-trauma related deaths during earthquakes. Increased stress and physical activity during and after an earthquake can cause cardiovascular deaths. In the 1981 Athens earthquake there was a 50 percent increase in deaths from myocardial infarction during the three days following the earthquake (Katsouyanni, 1986). Six of the 111 autopsied deaths in the 1999 Athens earthquake were cardiovascular in nature (Papadopoulos, 2004). Cardiac-related fatalities are a significant concern in earthquake situations where medical systems are overloaded and immediate access to emergency care may not be available. Other non-trauma deaths include pneumonia, shock, and exposure-related deaths. In the Kobe earthquake, one study reports 1.27 percent of overall fatalities were due to non-trauma related causes (Hengjian, 2000).

2.9.2 Causes of Earthquake Fatalities

Structural collapse is responsible for an overwhelming number of earthquake fatalities. It is estimated that 75 percent of total fatalities are a result of structural

[1] Patients with multiple injuries were counted more than once

collapse (Coburn, 1992). If the effects of secondary hazards such as fire, tsunamis, and landslides are not counted, structural collapse accounts for 90 percent of earthquake fatalities (Coburn, 1992). In the 1986 Earthquake in San Salvador, approximately 30 percent of fatalities can be attributed to the collapse of several engineered commercial or industrial buildings (Durkin, 1987). Even in developed countries where complete structural collapse is a relatively rare event, partial failure of structures is a major cause of earthquake fatality.

In the 1989 Loma Prieta earthquake, the majority of fatalities were a result of the collapse of the cypress freeway structure. Motor vehicle accidents accounted for 80 percent of fatalities, because of the cypress freeway and the Bay Bridge collapse (Centers for Disease Control, 1989). In the 1994 Northridge earthquake falling building parts were 8.36 (95 % CI=4.52-15.49) times more likely to cause a fatality rather than hospitalized injury and accounted for 71 percent of fatal injuries. The other causes of death during the Northridge earthquake were motor vehicle accidents, which caused 15.2 percent of fatalities, and falls, which caused 12.1 percent of fatalities (Peek-Asa, 1998).

In the Chi-Chi earthquake, at least 89 percent of deaths are directly attributable building collapse. Sixty-nine percent of deaths were a result of low-rise building collapse; 56 percent of those fatalities occurred in mudbrick buildings. The collapse of high-rise reinforced concrete buildings was a major factor in earthquake fatalities in urban areas (Tien, 2002). The remaining deaths were non-structural and caused by landslide as well as building contents, and medical conditions such as cardiovascular events.

2.9.3 Timing of Fatalities

Determining when fatalities occur is important in reducing casualties and prioritizing search and rescue and medical resources. Current research indicates that a majority of fatalities occur either instantly at the time of the earthquake or before medical attention can be received. In the 1988 Armenia earthquake, 88 percent of fatalities were reported in the first 24 hours (Armenian, 1997). This trend was also noted in the 1999 Athens earthquake where 93.7 percent of the 111 people autopsied were found dead at scene, this was attributed to long extrication times (Papadopoulos, 2004). In the 1985 Chilean earthquake where structural damage was less severe 35 percent of fatalities received medical attention and 65 percent died at the scene of the accident (Ortiz, 1986). In both the Northridge and Loma Prieta earthquakes, approximately 80 percent of fatalities occurred during or within minutes of the earthquake, which can be attributed to a few structural collapses accounting for a large percentage of injuries (Peek-Asa, 1998; Durkin, 1991).

2.10 Earthquake Injuries

There is a dearth of good epidemiology about specific injury types in earthquake situations. Typically, only a small percentage of the injuries are carefully reviewed and a complete picture of injury in an event cannot be ascertained. This is complicated by the fact that records may not be kept in the event of mass casualties. The majority of research about specific types of injury sustained during earthquakes comes from physicians' reports or surveys of hospitals. It is likely that minor injury is vastly underreported and the reliability of estimates of the incidence of more serious injury varies by event.

2.10.1 Medical Aspects of Earthquake Injury

Most injuries sustained in earthquakes are minor and require minimal medical attention. In all of the California earthquakes for which epidemiological analysis was performed the majority of injuries were minor and required medical treatment on an outpatient basis. It is assumed that in all earthquakes that there are a significant number of minor injuries, but in mass-casualty situations it is unlikely that these will be quantified. Aroni and Durkin in their 1985 survey of earthquake injury concluded that the majority of injuries in the California earthquakes in the late 1970's and early 1980's were injuries of the extremities including fractures, lacerations, and sprains (Aroni, 1985). This pattern continued in the Northridge earthquake, where of the hospitalized injuries, 53.6 percent were lower extremity, 18.8 percent were upper extremity, followed by spine, external (burn), head, face, and chest (Peek-Asa, 1998). The hospitalized injuries consisted primarily of fractures to the femur, pelvis, humerus, and radius. Of minor injuries sustained during the Northridge earthquake over 80 percent were cuts, bruises, and sprains (Shoaf, 1998). In the 1987 Whittier Narrows earthquake 40.5 percent of injuries were minor head injuries and in the 1989 Loma Prieta earthquake 55 percent of injuries were to the trunk or torso (Shoaf, 1998). The injuries in the Loma Prieta earthquake were around 60 percent strains, sprains, and contusions and 20 percent factures and lacerations (Durkin, 1993). Some estimates of minor injuries in California earthquakes were done through random sampling and the small sample sizes could lead to erroneous results.

Extensive surveys of non-hospitalized injuries are less common in international earthquakes, especially when fatalities are high. In the 1980 earthquake in Italy legs accounted for 39 percent of injuries, followed by head with 23 percent, chest with 19 percent, and arms with 16 percent (De Bruycker, 1985). The injuries sustained in 1980 Italian earthquake were 42.4 percent lacerations, 26.5 percent contusions, and 18.9 percent fractures (De Bruycker, 1985). In a cohort study performed after the 1988 Armenian earthquake, 2771 injuries were reported in a study population of around 7000. Of these 533 were fractures, 397 were crush injuries, and 646 were minor injuries such as superficial scratches (Armenian, 1997). In the 1985 Chilean earthquake where overall casualties were relatively low, 23.5 percent of injuries were contusions, 13.3 percent were lower extremity wounds, 12.3 percent were lower extremity fractures, 13.2 percent were wounds to the head, neck, or trunk, and upper extremity wounds and fractures made up another 13.4 percent of injuries (Ortiz, 1986). The 1995 Egyptian earthquake demonstrated similar patterns with the majority of injuries being fractures head and extremity injuries (Malilay, 1995).

2.10.2 Causes of Earthquake Injury

Unlike fatalities earthquake injury is not always predominately related to structural failure. In the Northridge earthquake, only 5.8 percent of injuries can be attributed to falling building parts such as beams, plaster, and chimneys. Fifty-five percent of injuries were caused by falls, 11.6 percent by furniture, and 1.4 percent by falling glass (Peek-Asa, 1998). Non-structural hazards are relatively unlikely to be a primary cause of mortality, but are overwhelming responsible for both serious and minor injuries. In developed countries and smaller earthquakes where the number of fatalities is likely to be relatively low, non-structural hazards account for the bulk of casualties.

2.11 Causes of Serious Long-term Injury

The type and severity of earthquake injury is extremely variable. The majority of earthquake injuries are comparatively minor and complete recovery can be expected after medical treatment is received. However, there are a number of conditions such as amputations, burns, neurological injury, and crush syndrome that can lead to permanent disability. Long-term disability can be extremely taxing on local health care systems and the insurance industry.

2.11.1 Crush Syndrome

Crush syndrome is the disintegration of muscle tissue (rhabdomyolysis) caused by prolonged continuous pressure on limbs (Visweswaran, 1999). This causes the release of potassium, phosphate, and myoglobin into the bloodstream, which can lead to hyperkalemia, renal failure, and cardiac arrhythmia (Eknoyan, 1993). In the 1988 Armenian earthquake of 1,000 people reportedly suffering from crush syndrome 323 of those developed renal failure (Aznaurian, 1990). Renal failure can lead to the need for long-term dialysis and can be a financial strain on the health care system.

Crush syndrome is a relatively common outcome in catastrophic earthquakes. It has been medically documented in the following earthquakes: the1980 earthquake in Southern Italy, the 1988 earthquake in Armenia, the 1995 Kobe earthquake, and the 1999 earthquake in Turkey (Dönmez, 2003). In a cohort study of the 1988 Armenian earthquake it was found that 11 percent of injuries were due to crush syndrome

(Armenian, 1997). Of 372 patients with crush syndrome following the Kobe earthquake, almost 75 percent was caused by injury to the lower extremities and 13 percent died (Oda, 1997).

2.11.2 Spinal and Neurological Injuries

Spinal and neurological injuries require extensive treatment and can lead to chronic disability. Injuries sustained during the 1976 earthquake in China caused over 2,200 people to become paraplegic (Chen, 1988). During the 1995 Kobe earthquake fractures of the limbs were relatively uncommon, but truck fractures of the spine, ribs, and pelvis were common when furniture and other heavy objects crushed people in bed (Maruo, 1996). Spinal and neurological injuries often require extensive and expensive treatment and can cause an undue burden on the healthcare system, especially in developing countries. Accurate predictions of numbers of head and spine injuries are of particular interest to the public health community and insurers because of the high cost and need for ongoing medical treatment.

2.11.3 Burns

Burn injuries can be life-threatening and chronically debilitating. One of the greatest post-earthquake threats is fire. The majority of the damage in the 1906 San Francisco earthquake was not related to the shaking itself, but to the fires afterward. Burn injuries continue to be a serious medical problem in earthquakes. In the 1995 Kobe earthquake, 504 deaths were listed as fire related and 2 percent of hospital admissions of injury patients were burn-related. (Nakamori,1997). In one 1999 Turkish earthquake most burn victims had scald burns of the lower extremities caused by hot water (Ad-El, 2001).

2.12 Hospital Usage

It is expected that an earthquake will cause increased usage of medical facilities. As a result, understanding and modeling the numbers and severity of earthquake injuries is important in properly allocating resources before, during, and after an event. Data from the 1976 Guatemalan earthquake, the 1988 Armenian earthquake, and the 1992 Egyptian earthquake indicates that hospital usage increases only during the first few days following an earthquake. One week after the earthquake hospital usage patterns were similar to normal (de Ville de Goyet, 1976; Noji, 1990; Mailay, 1992). This highlights the importance of having emergency medical teams that are able to respond quickly post-event. In the 1992 earthquake in Egypt, 70 percent of those patients injured during the earthquake were admitted within the first 36 hours (Mailay, 1992). After the 1994 Northridge earthquake, injury-related admissions peaked in the day following the earthquake after which they returned to normal range (McArthur, 2000). In the 1976 Guatemalan, 1985 Mexico City, the 1988 Armenian, and the 1989 Loma Prieta earthquakes, the peak in hospital admissions occurred on the second or third day as people were brought into medical facilities after being extricated from the rubble (de Ville de Goyet 1979; Sanchez-Carrillo, 1989; Noji, 1990; Pointer, 1992).

Other studies indicate that medical facilities continue to have heavy usage for a significant time period after the earthquake. Most often the injuries are less severe and may have not been immediately evident or they are illnesses related to displacement and poor sanitation. A study of utilization of disaster medical assistance team centers after the Northridge earthquake found that usage peaked 10 days following the earthquake (Leonard, 1995). The experience of a field hospital following the 1999 Turkish earthquake also noted continued patient usage more than a week following the earthquake, but the complaints had changed from acute injuries to illness and chronic disease (Bar-Dayan, 2000). Understanding the usage of medical facilities in the days following a catastrophic earthquake is a first step in properly allocating medical resources and minimizing death and injury severity.

2.13 Earthquake Casualty Modeling

Earthquake casualty estimation is a difficult task as earthquakes are notoriously unpredictable. The mechanisms for death and injury can vary significantly between events. In some earthquakes the bulk of casualties may result from secondary hazards such as fire, landslides, and tsunamis. In others the vast majority of the casualties will come from a few structural collapses. The addition of variables such as medical response, non-structural hazards, and cardiovascular and medical events only make the relationships more complex. It is far easier to predict casualty totals in larger earthquakes, as building collapse is likely to play a much greater role. The relationship between building collapse and earthquake death makes modeling earthquake mortality significantly more straightforward than modeling morbidity.

A number of different specific methodologies for modeling earthquake casualties proposed. However, almost all current probabilistic models are based on the general framework developed by Coburn and Spence (1992). They propose an event tree methodology that separates deaths from structural damage, non-structural damage, and deaths arising from secondary hazards. Structural damage is the dominant cause of death in most earthquakes. Deaths from structural damage are expressed in terms of the total number of collapsed structures of construction type, the population per building, the occupancy at the time of the earthquake, and the number of occupants trapped by collapse. The next level of the event tree determines the injury distribution at the time of collapse and the mortality post collapse stratified by whether an individual in trapped. Whether an individual is trapped and the survival rate are greatly influenced by search and rescue effectiveness, manpower, building type, collapse type, ambient environmental conditions, and numerous other factors.

This event tree methodology for earthquake casualty estimation relies on the strong correlation between building damage and morbidity and mortality. In smaller earthquakes the injuries rates are often driven by non-structural damage and casualty prediction can be difficult. In larger earthquakes casualties and fatalities in particular are driven by structural failures. Each of these parameters has a considerable amount of uncertainty associated with it. In addition, the resulting casualty rates are driven by building collapse assumptions.

This type of bottom-up approach to casualty modeling relies on structural engineering assumptions that can vary markedly between events and locations. There is not consistent data from which to estimate parameters such as search and rescue effectiveness and death rates given collapse. Each additional parameter introduces sizeable uncertainty and data for calibration has been limited. Casualty estimates using this type of methodology can be radically different than observed casualty numbers if any of the many assumptions required are incorrect. Despite these limitations, the event tree framework has historically been the primary methodology employed in developing earthquake casualty models.

The advent of GIS allowed for more complex spatial models to be applied to building inventories. In the early 1990s the US government funded the Earthquake Loss Estimation Methodology Study, which resulted in the development of HAZUS software. Commissioned by the Federal Emergency Management Agency (FEMA), HAZUS is a nationally applicable standardized software package that models building damage as a result of seismic events (National Institute of Building Sciences and Federal Emergency Management Agency, 1999). The HAZUS earthquake software maintains a building inventory of commercial, industrial, transportation, and other building facilities and characteristics such as building structure and frame in order to compute damage to building structure and contents. It also models secondary effects such as casualties, shelter needs, and economic losses. (National Institute of Building Sciences and Federal Emergency Management Agency, 1999).

The HAZUS model uses a 4 level injury severity scale. The classification system is similar to a triage system and the HAZUS levels are defined as follows:

1. Minor injuries needing basic medical care.
2. Injuries needing a greater degree of medical care but are not expected to progress to life threatening.

3. Injuries that pose an immediate life threatening condition.
4. Instantaneously killed or mortally injured.

The ambiguity in the injury definitions makes it difficult to duplicate results with other casualty estimation methods. In addition, the injury scales are immediate and cannot be used to determine outcome or medical costs.

The development of the HAZUS methodology was focused on building, infrastructure, and economic losses and is widely used in the emergency management community. HAZUS uses an event tree methodology and the casualty estimation is simply a multiple of building collapse probabilities. The primary focus of the development effort was in building damage rates. The casualty portion of the model is relatively unrefined and the estimated casualty rates have not been rigorously compared to historical data. The casualty rates used for complete collapse are shown in Table 2-10.

Table 2-10: HAZUS Casualty Distribution for Collapsed Buildings

Construction Type	Prob Of Collapse given 100 % Damage	Medical Aid Only	Hospitalized but not life threatening	Immediate Threat to Life	Death/Mortal Injury
W1	3.0%	40.0%	20.0%	3.0%	5.0%
W2	3.0%	40.0%	20.0%	5.0%	10.0%
S1L	8.0%	40.0%	20.0%	5.0%	10.0%
S1M	5.0%	40.0%	20.0%	5.0%	10.0%
S1H	3.0%	40.0%	20.0%	5.0%	10.0%
S2L	8.0%	40.0%	20.0%	5.0%	10.0%
S2M	5.0%	40.0%	20.0%	5.0%	10.0%
S2H	3.0%	40.0%	20.0%	5.0%	10.0%
S3	3.0%	40.0%	20.0%	3.0%	5.0%
S4L	8.0%	40.0%	20.0%	5.0%	10.0%
S4M	5.0%	40.0%	20.0%	5.0%	10.0%
S4H	3.0%	40.0%	20.0%	5.0%	10.0%

S5L	8.0%	40.0%	20.0%	5.0%	10.0%
S5M	5.0%	40.0%	20.0%	5.0%	10.0%
S5H	3.0%	40.0%	20.0%	5.0%	10.0%
C1L	13.0%	40.0%	20.0%	5.0%	10.0%
C1M	10.0%	40.0%	20.0%	5.0%	10.0%
C1H	5.0%	40.0%	20.0%	5.0%	10.0%
C2L	13.0%	40.0%	20.0%	5.0%	10.0%
C2M	10.0%	40.0%	20.0%	5.0%	10.0%
C2H	5.0%	40.0%	20.0%	5.0%	10.0%
C3L	15.0%	40.0%	20.0%	5.0%	10.0%
C3M	13.0%	40.0%	20.0%	5.0%	10.0%
C3H	10.0%	40.0%	20.0%	5.0%	10.0%
PC1	15.0%	40.0%	20.0%	5.0%	10.0%
PC2L	15.0%	40.0%	20.0%	5.0%	10.0%
PC2M	13.0%	40.0%	20.0%	5.0%	10.0%
PC2H	10.0%	40.0%	20.0%	5.0%	10.0%
RM1L	13.0%	40.0%	20.0%	5.0%	10.0%
RM1M	10.0%	40.0%	20.0%	5.0%	10.0%
RM2L	13.0%	40.0%	20.0%	5.0%	10.0%
RM2M	10.0%	40.0%	20.0%	5.0%	10.0%
RM2H	5.0%	40.0%	20.0%	5.0%	10.0%
URML	15.0%	40.0%	20.0%	5.0%	10.0%
URMM	15.0%	40.0%	20.0%	5.0%	10.0%
MH	3.0%	40.0%	20.0%	3.0%	5.0%

W= Wood, S= Steel, C= Concrete, PC= Pre-cast Concrete, RM= Reinforced Masonry, URM= Unreinforced Masonry
The numbers denote specific variations on the construction type
L= low-rise, M= mid-rise, H=high-rise

HAZUS assumes no fatalities or serious injuries for any building damage state other that 100%. Building damage states are benchmarked against the economic value of the building, which is not relevant to casualties. No fatalities are assumed for non-structural hazards or secondary hazards, as building collapse is the only mechanism considered. In addition, the casualty rates are simply multipliers of the building population as shown in Table 2-10. Injury and fatality rates are effectively held constant across construction class. In reality some buildings are designed to collapse with survival space and others, like URM, are not. In addition, the collapse rates are relatively similar across construction class even though event data indicates that certain building classes are significantly more likely to collapse. The HAZUS model is built using United States building classes and codes. There have been no large earthquakes in the United States upon which the model has been calibrated and the use of United States' construction classes limits the utility of the model for international earthquakes.

A similar automated loss estimated software, EPEDAT, is a proprietary model developed for California by EQE International, Inc. (Goltz, 1997). It employs real time seismic and building inventories in order to immediately generate casualty and loss estimates in order to help direct recovery efforts. In addition to the standard building probable loss estimates, ATC-13, also utilized in the HAZUS model, the EPDAT has a second set of calculations based on historical earthquake data. The integration of historical building response and casualty data with continued post-event analysis increases the efficacy of this model. It uses 40 structural types and 26 occupancy classes. The data source is ATC-13, similar to HAZUS, but the difference is in the output. EPEDAT gives a range for the number of casualties. The incorporation of historical data and refinement of the casualty estimates increases the utility of the model, but the primary event tree structure is similar to HAZUS and the relationship between building damage states and casualties is still the key parameter. In addition, it is only applicable to California construction classes.

Due to the large amount of uncertainty associated with key parameters, the number of assumptions needed to parameterize the model, and the fact that the model is multiplicative; the end result of the event tree approach is often not consistent with observed event data. Despite these shortcomings, casualty modeling has primarily been done by structural engineers and so the event tree framework has dominated earthquake casualty modeling.

2.14 The Chi-Chi Earthquake

2.14.1 Introduction

A magnitude 7.6 earthquake struck the central region of Taiwan on September 21, 1999, at 1:47 a.m. local time. (September, 20, 5:47 p.m. UTC). The earthquake's epicenter was located near the town of Chi-Chi, in Nantou County and was at a depth of 8 km. The earthquake was located in the northern part of the Chelungpu Fault and generated a surface fault rupture of about 100 km in length (Uzarski, 2001). The epicenter was in the center of Taiwan and the whole country and its population of 22 million people were affected by strong shaking intensities and peak ground accelerations of 0.30 to 0.50 g and peak ground velocities of between 40 and 80 cm/sec (Lee, 2000).

The more densely populated northern and western parts of the island experienced the most severe shaking and a large number of structures were affected by shaking and surface ruptures. There were at least 2,400 fatalities and 11,000 injuries. The Chi-Chi earthquake caused extensive structural damage resulting in the destruction of over 30,000 housing units and severe damage to another 25,000 leaving, at least 100,000 people homeless (Uzarski, 2001). A number of important structures such as bridges, dams, tunnels, and transmission towers were destroyed or damaged by strong shaking. Twenty-four hours after the earthquake nearly one quarter of Taiwan was still without power. Numerous landslides hindered rescue efforts especially in the mountainous areas of central Taiwan. The total economic loss was over $30 billion US dollars.

2.14.2 Geologic Effects

Taiwan is located at the convergence boundary between the Philippine Sea Plate and the Eurasian Plate. Seismic activity in the area created the steep range of mountains that run north-south through Taiwan. The mountain range divides the gently sloping western half of the country, which has 90 percent of Taiwan's residents from the rugged mountainous eastern half. In the northern and eastern part of the country, large magnitude seismic events are common. The western part of the country is dominated by less frequent and smaller earthquakes with a shallow focal depth. Forty active faults generally running north-south have been identified and mapped as shown in Figure 2-3.

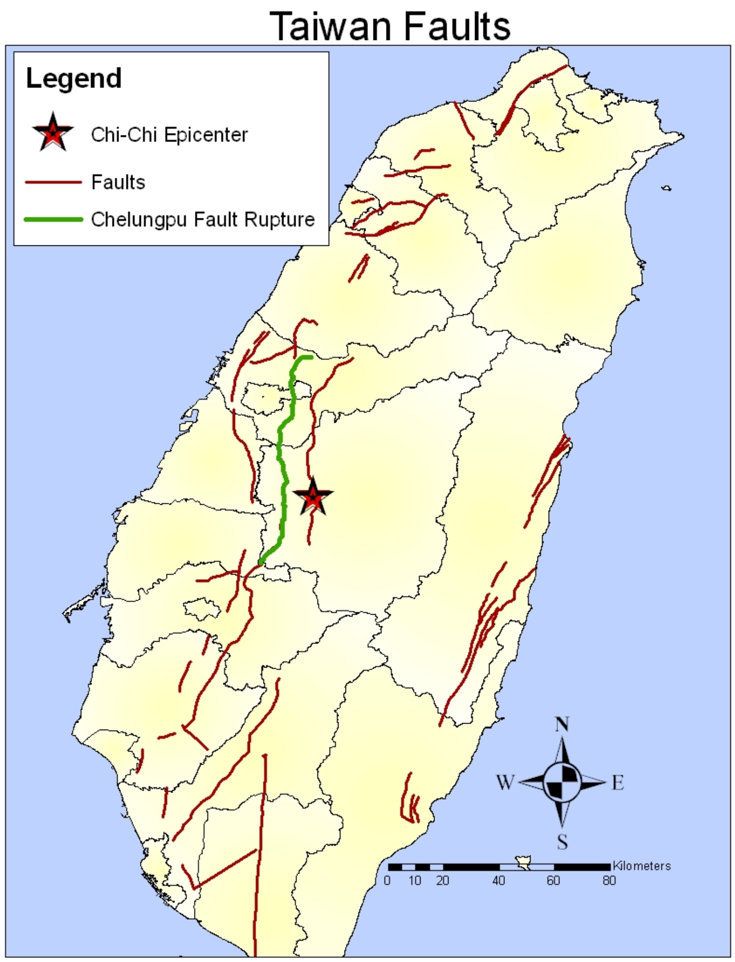


Figure 2-3: Map of Active Faults in Taiwan

The Chi-Chi earthquake was caused by a 100 km north-south rupture of the Chelungpu fault. The epicenter was located about 15 km from the southern end of the fault and the rupture propagated primarily in a northerly direction. Chelungpu fault is an inclined thrust fault, which dips at a 30 degree angle over an area of approximately 20 kilometers. The hypocenter of the 1999 Chi-Chi earthquake is approximately 8 km deep almost directly below the Shuangtung fault.

In total, the magnitude 7.6 main shock lasted approximately 30 seconds. The earthquake was followed by around 10,000 aftershocks the largest of which was a magnitude 6.8. The earthquake generated more than 1,800 landslides to the east of the fault, 3 of which caused significant casualties (RMS, 2000).

2.14.3 Casualties

The 1999 Chi-Chi earthquake was the most severe earthquake to hit Taiwan in the 20th century, resulting in around 2,500 deaths and 11,000 injuries. Mortality was concentrated in the areas of high ground-shaking closest to the fault rupture. The earthquake occurred when most people were sleeping, delaying evacuation and emergency response. The time of the earthquake also exacerbated the situation because residential construction, especially in the rural areas, is not as seismically sound as commercial buildings. The most severe ground shaking was in a relatively poor rural part of the country which has 8 physicians per 10,000 people compared with the capital city Taipei, which has 3 times that number (Liang, 2001).

The mortality was highest in the elderly. The fatality rate was comparable between males and females (Chan, 2003). The odds of death were increased for those with a lower SES and those with a physical disability (Chou, 2004). However, this may be an artifact of the fact the ground-shaking was strongest in a rural area with lower SES and the analysis was not adjusted for geographic location.

The most common cause of death was asphyxiation accounting for 34 percent of fatalities (Liao, 2005). The other deaths were attributable to traumatic injury such as collapse related head injury, complications to injuries of the truck or extremities, chest injury, crushing injury, and skull, spinal, or limb fracture (Liang 2001; Chan 2003). The majority of deaths occurred immediately or within the first 24 hours following the earthquake. No published individual level epidemiologic analyses were available for injuries, however it was estimated that 90 percent of injuries were head injuries, open wounds, or fractures (Chen, 2003).

CHAPTER 3 : EVALUATION OF THREE METHODS OF MODELING THE SPATIAL DISTRIBUTION OF EARTHQUAKE FATALITIES

3.1 Introduction

The importance of the problem

Earthquakes are by nature a spatial phenomenon and casualties are dependent on the origin and pattern of the earth's movement. The importance of data driven spatial models of earthquake casualties to casualty estimation, emergency planning, the appropriate placement of lifeline facilities, and search and rescue prioritization has routinely been discussed. However, few attempts have been made to actually develop spatial models based on real events. This paucity reflects limitations of post-earthquake data collection, especially after large events, and also the lack of multi-disciplinary research between seismologist, geologists, engineers, and public health researchers. The high quality seismic, building, and casualty data obtained during and after the Chi-Chi earthquake provides a unique opportunity to test the hypotheses about the spatial distribution of earthquake casualties using real event data.

The limitations of existing work

Despite its tremendous importance to the reduction of earthquake-related morbidity and mortality, the spatial distribution of earthquake casualties has been inadequately quantified. One reason is the difficulty of finding a simple accurate framework through which to model a complex event. Seismologists have demonstrated that simple exponential models can be used to characterize the loss of seismic energy as waves propagate outwards from the hypocenter. However, the location of the earthquake is not the only determining factor. The depth, rupture pattern, and focal mechanism of earthquake all influence the propagation of seismic energy.

Until now two primary spatial frameworks have been proposed to look at the distribution of damage and casualties from an earthquake. These are the concentric circle model centered on the epicenter and axial variation model centered on the surface rupture. These models represent only basic earthquake rupture patterns. The overwhelming majority of high damage earthquakes result from more complex fault ruptures. If response, recovery, and mitigation decisions are based on inappropriate or overly simplistic models it is likely that there will be a significant misallocation of resources or a delay in response.

Hypothesis and introduction to the model that will be proposed

Seismic, casualty, and population data from the Chi-Chi earthquake will be used to evaluate predictive ability of three different models, each based on its own centering variable: epicenter, surface rupture, and maximum coseismic slip. The data will be used in order to illustrate the shortcomings of traditional models in complex ruptures. In addition, the predictive ability of spatial distance-based models will be compared with those of intensity-based models. It is hypothesized that a distance decay model centered on maximum coseismic slip would provide a simple framework through which to conceptualize the spatial distribution of earthquake fatalities, and will predict casualties more accurately than models that are currently being used by the public health and emergency management community.

Statement of the goal of the analysis

The goal of this paper is to describe a better structure for conceptualizing and modeling the spatial pattern of earthquake fatalities in order to more accurately reflect reality and increase the utility of spatial models in planning and response. By building seismologic principles into the base framework, a model can be created that will be applicable to complex faulting systems. Coseismic slip is the pattern of crustal movement that occurs during a seismic event, a key concept in understanding and modeling faulting structures. By using the maximum coseismic slip of the rupture as the centering point for an axial variation model, a base model can be developed that will improve casualty prediction for complex earthquakes, not just those with a simple rupture pattern. This paper will attempt to develop a model that can be coupled with population data, building inventory estimates, and building damage curves to provide a simple framework through which to estimate earthquake-related casualties.

3.2 Methodology

3.2.1 Background

Earthquakes are complicated phenomena and no single variable accurately describes the entire event. The energy propagation from the event is determined by the magnitude, depth, geologic conditions, and the mechanism. Earthquakes occurring on thrust faults have different characteristics than those on strike-slip fault zones or normal fault systems. This makes it difficult to find a single seismic variable upon which to center a casualty model.

Seismologists can model and predict the likely magnitude and mechanism of an earthquake based on the tectonic conditions in the area. Casualty models can be developed based on seismological models given appropriate input variables. No spatial reference points upon which to base a model for casualty prediction have been rigorously evaluated, but the two most commonly used by non-seismologists are the epicenter and surface rupture. In the public health community the epicenter is typically the only geographic reference point utilized.

Definitions and explanations (centering parameters, decay functions, spatial modeling)

The USGS defines the epicenter as "the point on the earth's surface vertically above the hypocenter (or focus), point in the crust where a seismic rupture begins" (USGS, 2005). However, because faults are planar surfaces the energy release does occur concentrically from a central point. Most large earthquakes are not point releases of energy, but rather result in a rupture along a section of the fault.

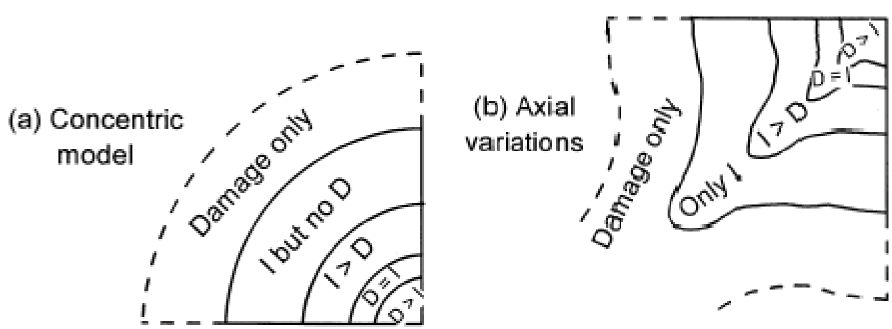
The centering parameter is the spatial reference point that serves as the base of a spatial casualty model. From that a pattern of decay, the functional form that determines the rate at which the casualty rates change as distance increases from the centering parameter increases, is determined.

Once an appropriate centering parameter and decay function have been selected, the spatial model is further developed by calibrating the modeled death and injury rates against real events. Additionally, nodal variations, specific regions with risk dissimilar to the surrounding regions, should be modeled in order to create a model that accurately enough reflects reality to assist in mitigation and response. The resulting calibrated equations, known as casualty vulnerability functions, can be applied to seismic, geologic, population and construction data in order to develop a spatial risk map. The criteria will depend on the application of the model, but casualty modeling requires a balance between creating a model that accurately reflects reality and doing so in the timeframe and with the data available to inform decision making.

Limitations of current models

The majority of public health studies of earthquakes fail to account for the importance of geographic reference points when evaluating risk factors for casualties. For those that do include a spatial element they typically only use the epicenter as a spatial reference point. The nature of seismic rupture makes a concentric circle model positioned around a point-based epicenter too simplistic for all but a handful of earthquakes; most of which lack the intensity to cause significant mortality or morbidity.

Alexander (2000) proposes that modifications to the basic concentric circle model can be made to account for damage elongated around a fault trace. This model would account for anisotropic variations in earthquake casualties, known as the axial variation model. Figure 3-1 below depicts the concentric circle model and axial variation model as shown in Alexander (2000).



D = deaths I = injuries

Figure 3-1: Currently Proposed Spatial Models of Earthquake Casualties

The axial variation models are centered on the surface rupture. Although, this is an improvement over the epicenter the Chi-Chi earthquake demonstrates some of the issues associated with using the surface rupture. Not all earthquakes result in a surface rupture. In addition, there is often asymmetry in ground motion between the hanging wall and footwall sides of the fault, especially in thrust faults. The Chelungpu fault rupture in the Chi-Chi earthquake initiated at the epicenter and propagated along the fault primarily in a north south direction. The result was thrust and left-lateral displacements ranging from 1 meter in the south to 10 meters in the north (Central Geologic Survey, 1999). As is typical with thrust faults, the ground motions were highly asymmetrical along the surface rupture. The footwall areas along the west side of the surface of the fault had notably lower peak ground acceleration (PGA) and intensity. The east hanging wall side experienced significantly greater intensities and subsequently much greater damages.

Figure 3-2 illustrates the asymmetry in ground motions between the hanging wall (east) and footwall (west) sides of the fault in the 1999 Chi-Chi earthquake. This discrepancy is well-documented and can result in double the ground motion when compared to a vertical fault (Ogelsby, 1998). Figure 3-3 shows a simple diagram of a dipping fault analogous to the Chelungpu fault, which ruptured in the Chi-Chi earthquake. The spatial models that use surface rupture are sometimes appropriate for vertical strike-slip faults, such as the San Andreas in California, where the large asymmetries in ground motion are much less likely to occur. However, non-vertical (dipping) faults predominate in earthquake prone urban areas such as Los Angeles, Japan, Central and South America, Turkey, Iran, and Pakistan.

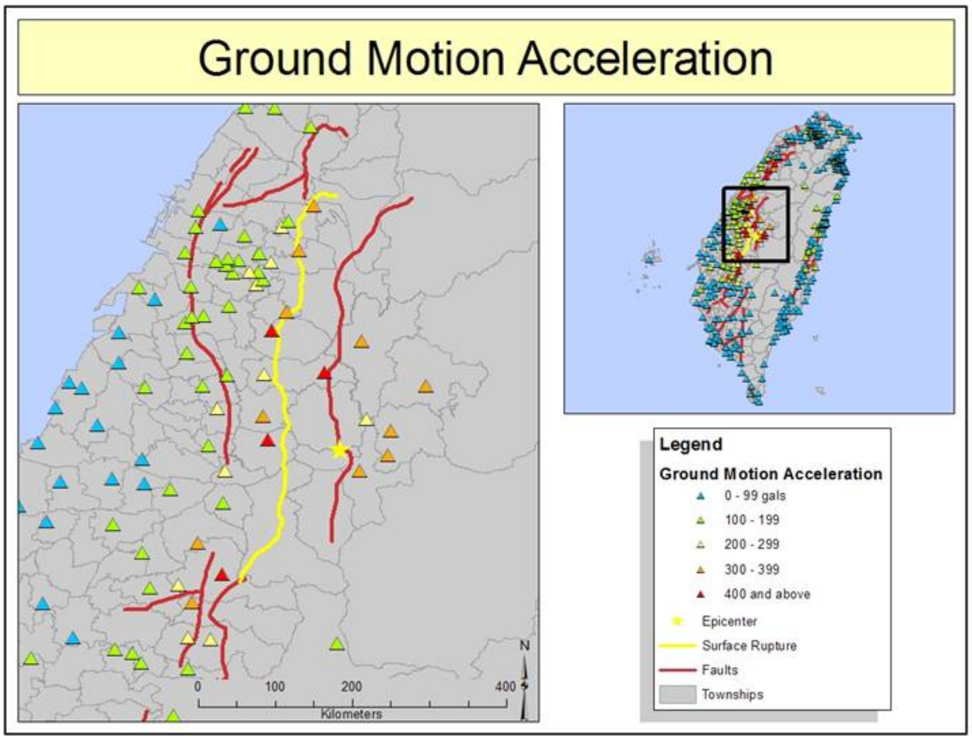


Figure 3-2: Ground Motions Recorded During the Chi-Chi Earthquake

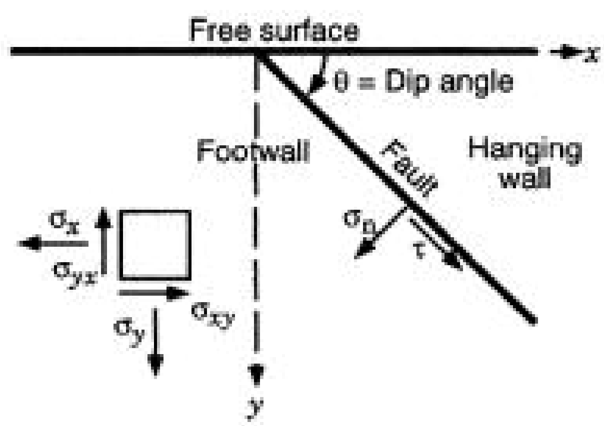


Figure 3-3: Diagram of a Dipping Fault, Taken from Ogelsby, 1998

Proposed Model Centering Parameter – Maximum Coseismic Slip (Rationale and Applicability)

Models using the epicenter and surface rupture inadequately characterize the complexity and variety of faulting structures. Instead, this paper proposes using the seismological concept of maximum coseismic slip as the centering parameter which should allow all fault structures to be more appropriately modeled. Coseismic slip is the relative displacement between the two blocks that bound a fault, which occurs during an earthquake. It is a simple concept which can be measured or modeled for any earthquake. The earthquake model describes the pattern of coseismic slip and by using it as the base for the casualty model seismological principles that take complex ruptures into account are built in to the fundamental structure of the casualty model. This approach allows for a simple framework that can be applied to any earthquake.

Figure 3-4 shows horizontal measurements of the coseismic displacements of a dense GPS station network in the vicinity of the Chi-Chi fault. A simple 3-dimensional fault surface model with coseismic slip vectors varying over a uniform grid fits the observations within their uncertainties (Johnson and Segall, 2004). It is evident from the diagram that the area of maximum slip runs parallel to the fault, but is east of the hanging wall side of the fault towards the epicenter. Using this as a reference point for the center of the model, a distance-decay relationship can be created to more accurately reflect the spatial distribution of casualties.

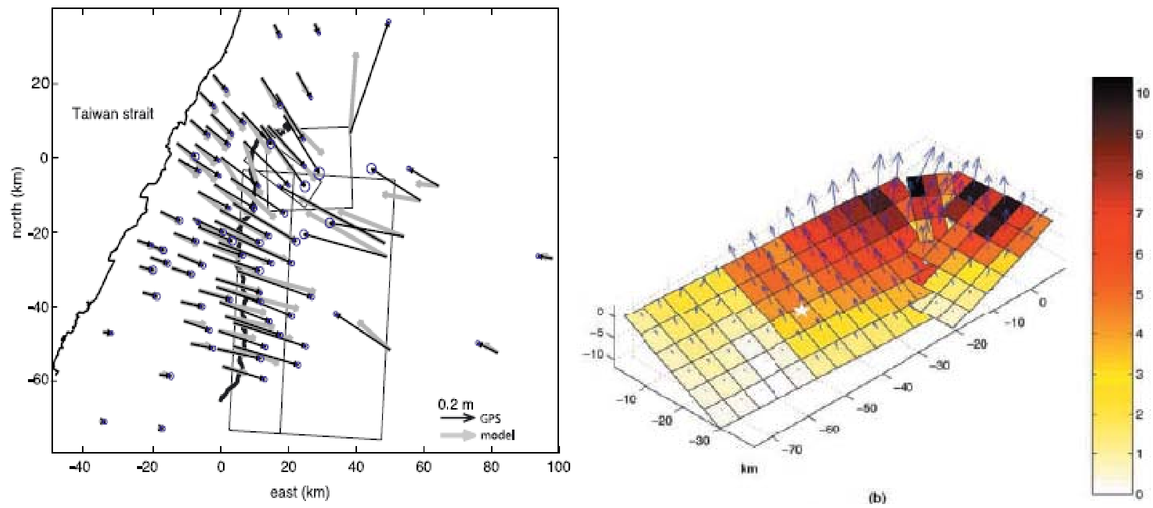


Figure 3-4: Coseismic Slip Diagram for the Chi-Chi Earthquake, Taken from Johnson, 2004

3.2.3 Model Decay Function

Once an appropriate centering parameter has been determined to serve as the base of a spatial casualty model it is necessary to determine an appropriate pattern of decay. The pattern of decay is the functional form that determines the rate at which the casualty rates change as the distance from the centering parameter increases. A variety of different decay functions have been proposed to characterize the spatial relationship of earthquake casualties as illustrated in Figure 3-5.

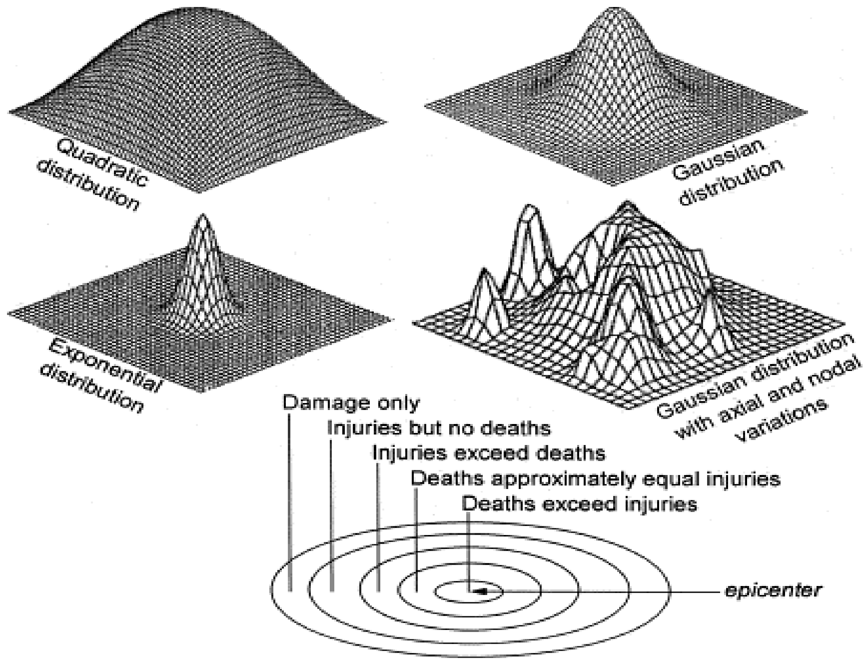


Figure 3-5: Spatial Models of Earthquake Casualties, Taken from Alexander, 2000

Rationale for selecting the decay function

Seismologists have demonstrated that simple exponential models can be used to characterize the loss of seismic energy as waves propagate outwards from the hypocenter (Howell and Shultz, 1975). An overwhelming majority of the casualties in earthquake are related to building collapse and building collapse is highly correlated to ground-shaking, it follows that casualty distribution may decay similarly to the ground motion. Many factors complicate this assumption, including geologic substrate properties, building characteristics such as material, density, seismic building codes, individual and response factors, such as the ability to evacuate and search and rescue effectiveness. In addition, events in specific geographic area with large loss of life such as high-rise collapse and landslides make it more difficult to model the variation in an event using a simple decay function. The factors listed above highlight the potential need for nodal variation within the chosen casualty vulnerability function.

3.2.4 Model Evaluation and Comparison with Existing Models

Study goal and design

The goal of this study is to evaluate the ability of three different models to predict risk of death or injury for each villages or townships based on their spatial location, following the Chi-Chi earthquake. The study design employed is a geographic correlation study, which can be viewed as an ecologic study specifically utilizing spatial relationships. The unit of analysis is the village or township, the outcome of interest is the corresponding group-level mortality or injury risk, and the predictor of interest is the geographic location of the village or township in relation to the earthquake.

The three models of interest are each distance-based and assume a decay relationship derived from a logistic model. The epicenter model consisted of a concentric circle model centered on the epicenter as depicted in Figure 3-6. The surface rupture model is an axial variation model centered on the surface rupture as depicted in Figure 3-7. The epicenter and surface rupture models are representative of previously proposed spatial models of earthquake casualties. Figure 3-8 represents the newly proposed decay function based on use of coseismic slip.

Sources of data

In order to evaluate the predictive abilities of the coseismic slip model and to compare it to the epicenter and axial variation models, data from the Chi-Chi earthquake were utilized. The Chi-Chi earthquake has excellent casualty data, arguably better than that recorded following any other major earthquake. In most earthquakes, no accurate record of the spatial location of those killed or injured is available. Casualty data were obtained by request from the National Fire Agency of Taiwan in Chinese. These data included counts of fatalities, injuries, missing, rescued, and partially and totally collapsed buildings for all townships that sustained earthquake damage. Fatality data for each village were obtained from Taiwan's National Center for Health Statistics in Chinese. These casualty data provide counts of fatalities by village and by townships; for injuries counts are available only for townships. Data from the 2000 census were transcribed from published government documents on the township-level. Village-level population data included population only (Tien, 2002; Lee, 2002; National Fire Agency). The data were mapped using ArcGIS 9.1. The distance between the epicenter, surface rupture, area of maximum coseismic slip and the centroid of each township and village was calculated using ArcGIS 9.1.

Taiwan has a total of 359 townships with a mean population of 61,445 and a range of 1,723 to 529,025. The majority of townships have populations under 15,000 and the mean is heavily influenced by a small number of townships in large cities such as Taipei. Within the townships there are approximately 7,750 village regions with a mean population 2,844 and a range of 28 to 31,155 based on 2000 census data.

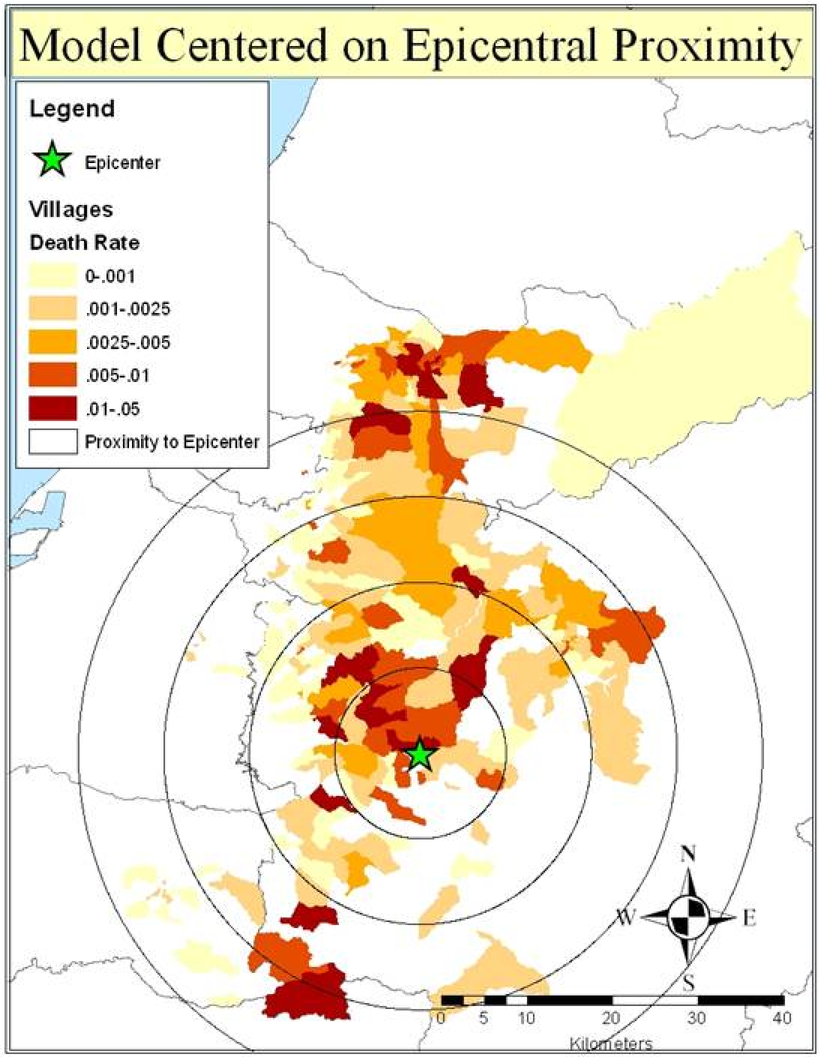


Figure 3-6: Epicenter Model

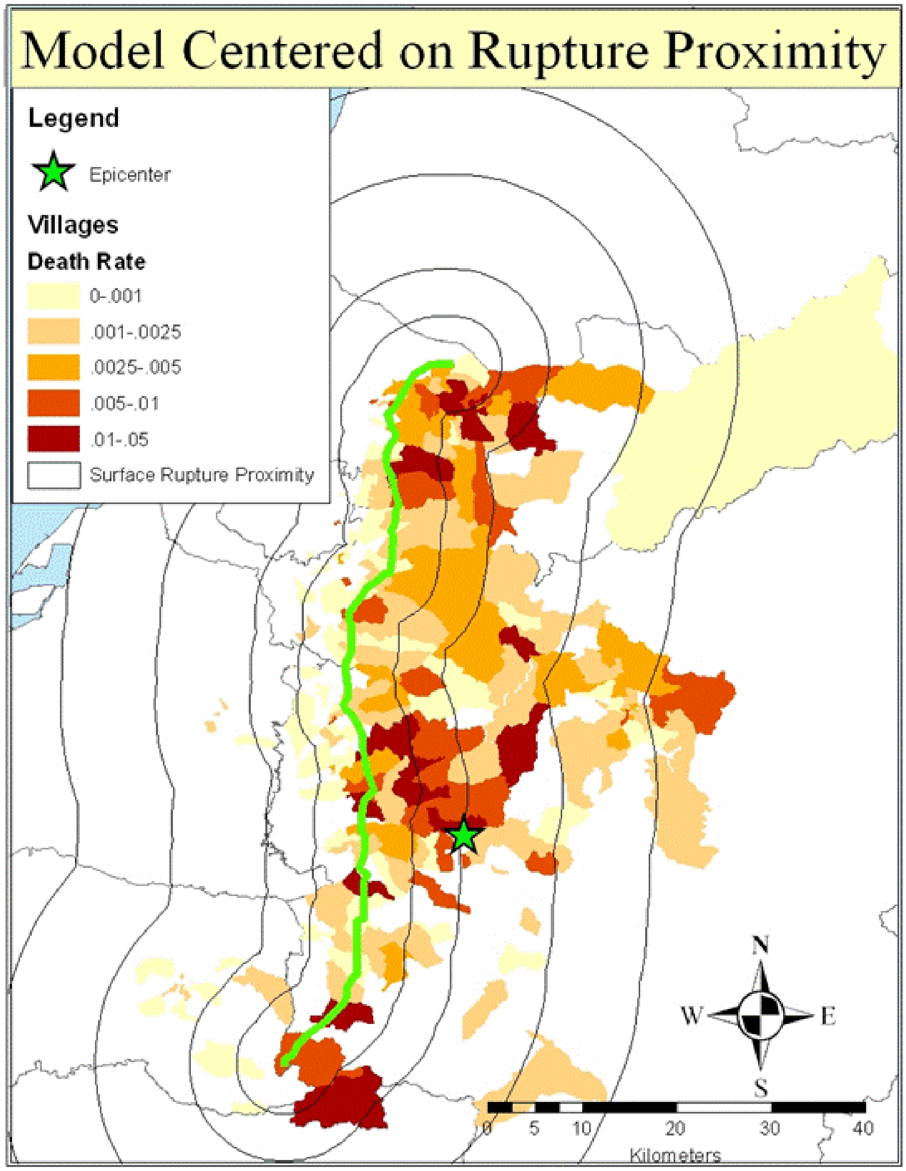


Figure 3-7: Surface Rupture Model

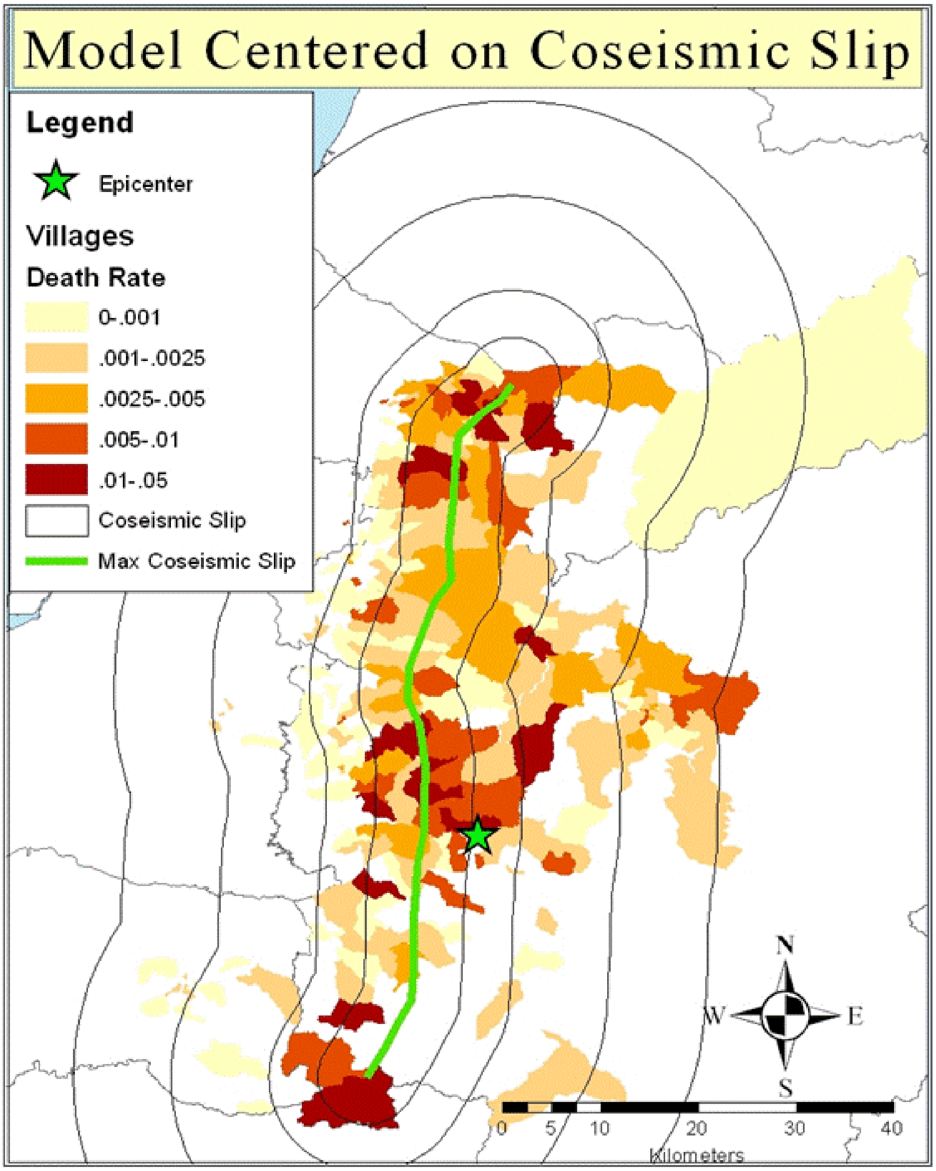


Figure 3-8: Coseismic Slip Model

A logistic regression model was fit to the Chi-Chi earthquake village (or township) level casualty data for the 3 centering parameters. The model was fit using a generalized estimating equation approach. Clustering by village (or township) was accounted for with an exchangeable correlation structure and robust variance estimation.

The probability of death for people in each geographic region was modeled as a function of the distance from the centroid of the region to the surface rupture, maximum coseismic slip, or epicenter. The models are Logit $(P(Y_{1i,2i}=1| x_i)) = A_i + B_i*x_{i.}$ where, Y_{1i} is the number of deaths, Y_{2i} is the number of injuries and x_i is distance from the centroids of village i or township i for each of the 3 centering parameters. Clustering within each geographic region was accounted for assuming an exchangeable correlation structure. Other correlation structures were examined in sensitivity analyses and resulted in no significant changes to the results. A vulnerability function was obtained from the coefficients A and B. A is the intercept term corresponding to the fatality measure at a distance of 0 km from the area of maximum coseismic slip and B is a measure of the decay of fatalities by distance.

Measures of goodness of fit and statistical criteria

The data were analyzed in SAS version 8.2 where point estimates and confidence intervals were obtained using logistic regression and the generalized estimating equation approach. Spearman correlations between observed and expected counts were calculated as goodness of fit measure. The expected counts were calculated by multiplying the population at risk in each area by the probabilities predicted by the model. Analysis of residuals, bivariate plots, and ease of use and simplicity were also considered in determining the most appropriate model.

The model is intentionally simple and the distance variable does not account for all of the variation. In sensitivity analyses using a random effect for village (or township) to account for geographic clustering resulted in similar point estimates and the same conclusions about significance and model fit. In addition, the Poisson and negative binomial examined as an alternative distributions. Since morbidity and mortality in an earthquake is a rare outcome, the results of the regression using the binomial distribution were nearly identical to the results using the Poisson distribution with the log of the population as the offset.

3.3 Results

Township-level results for the comparison of the 3 models fatalities- fit statistics and graph

Table 3-1 and Figure 3-9 show the results of a township-level regression analysis for fatalities. The distances from the centroid of the township to the epicenter, surface rupture, and maximum coseismic slip were used as the model variables. The data included all townships that sustained earthquake-related damage. The coseismic slip model has a better fit than either the epicentral or surface rupture model as measured by both the confidence interval and the Spearman ρ.

Table 3-1: Township-Level Results from the Regression Analyses for Fatalities

Parameter	Intercept (95% CI)	Coefficient (95% CI)	Spearman ρ
Coseismic	0.22% (0.09%, 0.55%)	-0.111 (-0.207, -0.014)	0.48
Epicenter	0.30% (0.10%, 0.88%)	-0.042 (-0.082, -0.001)	0.38
Rupture	0.09% (0.05%, 0.16%)	0.021 (-0.087, 0.046)	0.09

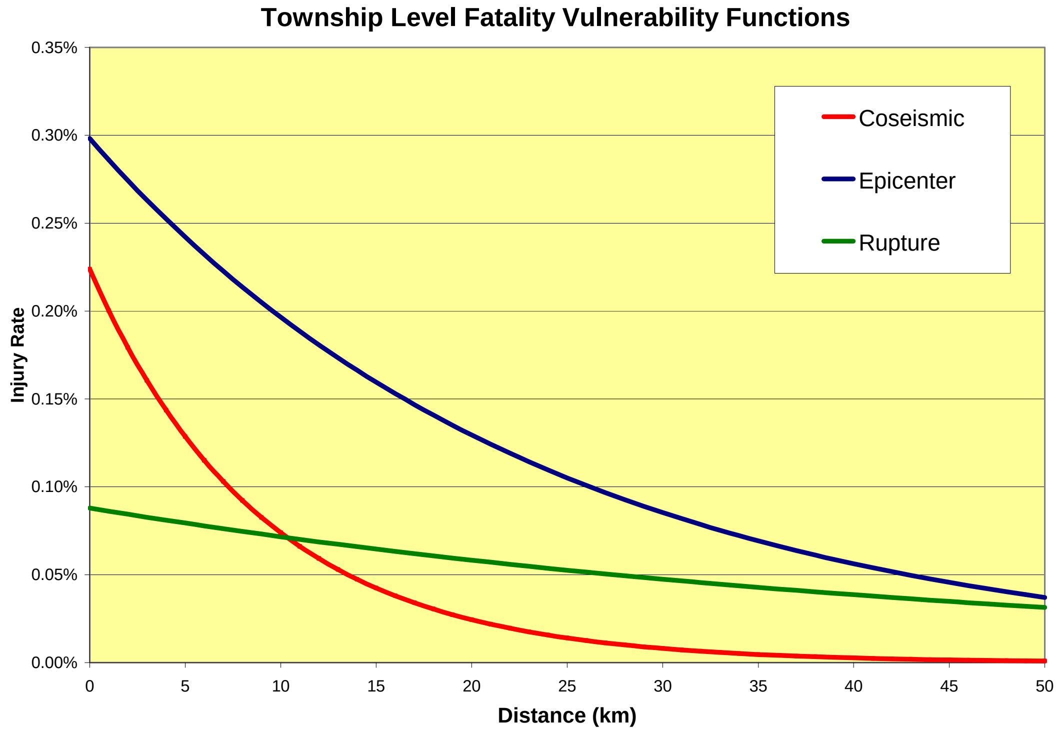


Figure 3-9: Comparison of Township-Level Fatality Vulnerability Functions for the 3 Models

Township-level results for the comparison of the 3 models injuries- fit statistics and graph

A similar analysis was performed for injuries also on a township-level. The results are shown in Table 3-2 and Figure 3-10. The coseismic model is the only one with a confidence interval that does not include 0 and the coseismic model fit is better than either the epicenter or surface rupture model as measured by the Spearman ρ. Visual inspection points out the unsuitability of the surface rupture model as risk increases with distance from the rupture.

Table 3-2: Township-Level Results from the Regression Analyses for Injuries

Parameter	Intercept (95% CI)	Coefficient (95% CI)	Spearman ρ
Coseismic	1.08% (0.31%, 3.73%)	-0.124 (-0.227, -0.02)	0.58
Epicenter	0.61% (0.22%, 1.67%)	-0.018 (-0.063, 0.027)	0.38

Rupture	0.13% (0.2%, 0.93%)	0.088 (-0.082, 0.015)	0.33

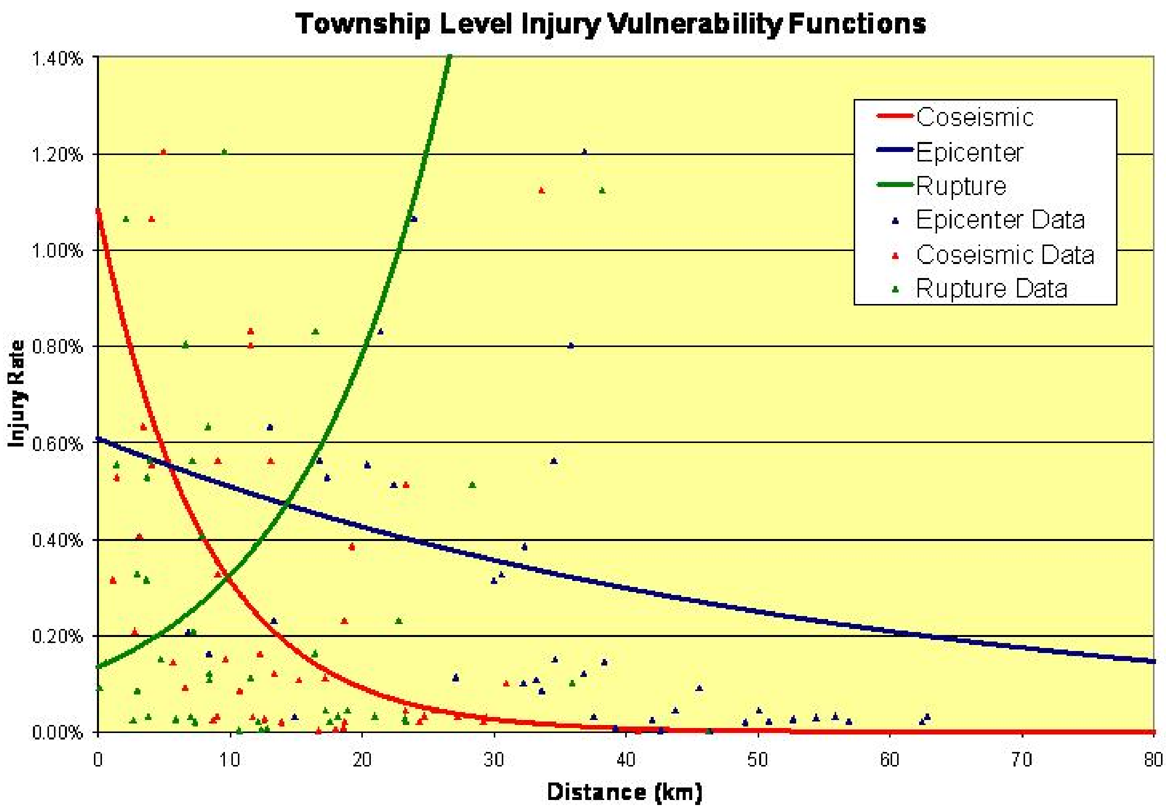


Figure 3-10: Comparison of Township-Level Injury Vulnerability Functions for the 3 Models

Village-level results for the comparison of the 3 models fatalities- fit statistics and graph

Village is the smallest geographic unit with available casualty data. Casualty data were available for fatalities only. The village-level analysis provides the most accurate comparison for fatalities and has the least aggregated data. The average population in a village region in 3,300 compared with 87,000 in a township. The village-level results are in Table 3-3 and Figure 3-11. The coseismic model is the only one with a confidence interval that does not include 0 and the model fit is much better for the coseismic model than either the epicenter or rupture as measured by the Spearman ρ (fit was also better based on the Pearson ρ and AIC, data not shown). As illustrated in Figure 3-11 the coseismic slip model decreases by 15.4% per km shift away from the line of maximum coseismic slip. The risk of fatality increases by 0.9% per km shift away from the line of maximum coseismic slip for the surface rupture model and for the epicenter model it is nearly constant with distance and decreases by 1.4% per km. A model using either of these functions would result in poor prediction of the fatality distribution and an overestimation of fatalities for the earthquake. These differences highlight the importance of the centering parameter in modeling casualties in complex fault ruptures. Figure 3-12 illustrates the relationship between village-level casualties and the vulnerability function. There were 536 villages included in the analysis and there is significant variation in fatality rates between the villages.

Table 3-3: Village-Level Results from the Regression Analyses for Fatalities

Parameter	Intercept (95% CI)	Coefficient (95% CI)	Spearman ρ
Coseismic	0.43% (0.26%, 0.70%)	-0.154 (-0.217, -0.09)	0.259
Epicenter	0.18% (0.10%, 0.34%)	-0.014 (-0.036, 0.008)	0.056
Rupture	0.11% (0.08%, 0.15%)	0.009 (-0.007, 0.024)	0.022

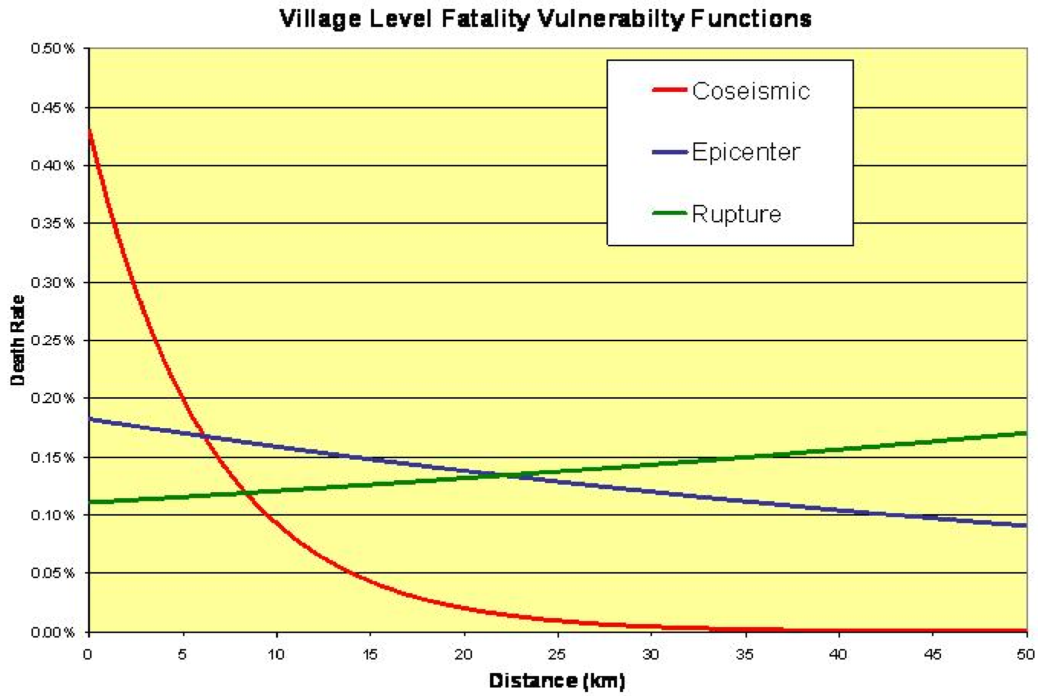


Figure 3-11: Comparison of Village-Level Fatality Vulnerability Functions for the 3 Models

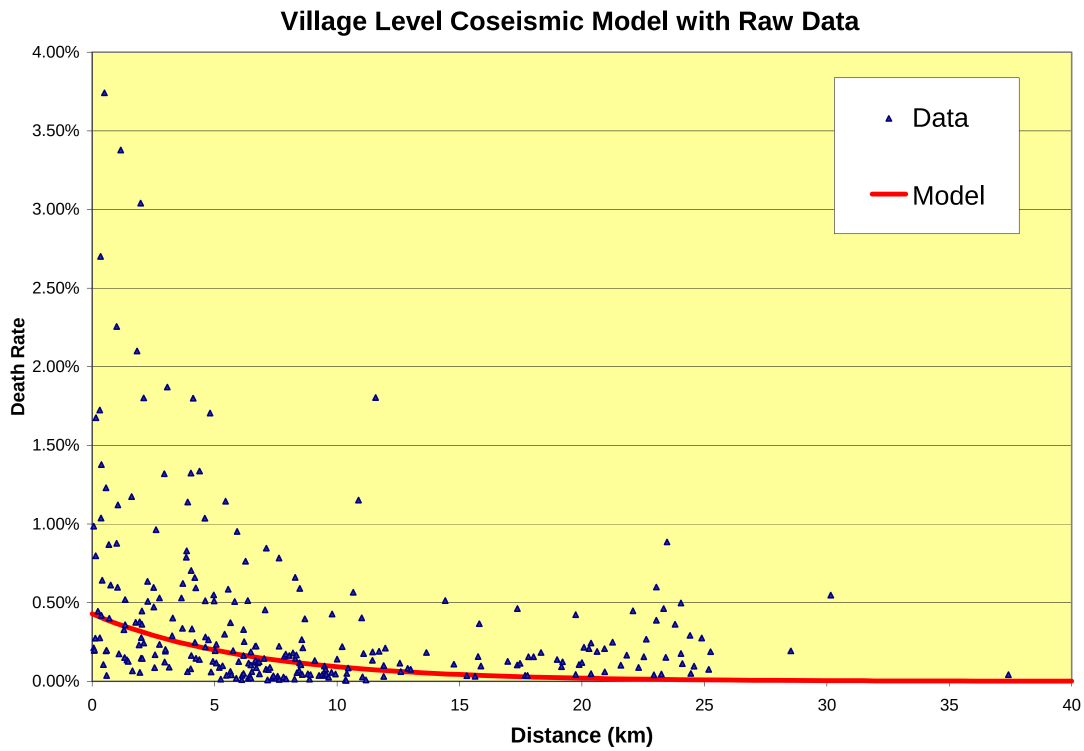


Figure 3-12: Village-Level Fatality Vulnerability Function and Raw Data for the Coseismic Model

The vulnerability functions and fit statistics are similar regardless of the method used and geographic aggregation. Both regression analyses shown above demonstrate the fact that maximum coseismic slip results in a better fit visually and statistically than either the epicenter or surface rupture models irrespective of geographic aggregation or methodology.

3.4 Discussion

Summary of the comparisons of key results modeling approaches

The coseismic slip model clearly predicted casualties better than either of the other models considered. For both injuries and fatalities and in both village-level and township level analyses, the fit of the maximum coseismic slip model was better than either the epicenter or surface rupture model. This impression was supported by correlations coefficients, by plots, by visual inspection and by plausibility of the fitted models.

Village-level data required less geographical aggregation, which is preferred, but were only available near-fault. The model for village-level fatalities has a slightly larger intercept and faster decay than the township level model, presumably because the lower degree of aggregation. Townships are geographically large and due to the aggregation the vulnerability functions for all three analyses are more similar than when a smaller unit of geographic aggregation was considered.

The township-level data were used as a comparison and to include injury data that were not available on the village-level. There were several hundred deaths due to high-rise failure from long-period ground motion that were only accounted for in the township-level data. As a result, the township-level functions decay at a slower rate and an alternative method separately accounting for this nodal variation may be more appropriate. In addition, injury data were available on a township-level. Injury estimates are more difficult to accurately model, because what is counted as an injury is often not consistent from one event to another. Despite the differences in geographic resolution and analysis method the overall conclusion remained the same; using coseismic slip as a centering parameter results in a better model fit than using either the epicenter or surface rupture.

Strengths and limitations of the data

Higher resolution geographic data will result in greater the accuracy of the spatial models, but they may not be ideal because of the time required to compile and analyze the data. There are a number of issues associated with collecting accurate data in a mass casualty situation. The location of a person killed or injured is most often attributed to their home address, which in earthquakes that occur in the middle of the night like Chi-Chi is likely a reasonable assumption. Some proportion of the population is likely to not be at their home address at the time of the earthquake. Denominator data, in this case census data, also assumes home address. In addition, it is not collected every year and the exposed population at the time of the event is likely to differ from census estimates. The data used in this analysis is from an official governmental source and is the most comprehensive data available, however it is likely that some deaths and injuries were missed or misclassified as earthquake-related since the priority is patient treatment and triage not record keeping.

Geographic aggregation and ecologic study

The data collected during the Chi-Chi earthquake is likely the best spatial data collected in a mass-casualty earthquake and it is unlikely that very high resolution geographic data would be available in a mass-casualty earthquake, especially in real time. The limitations in the geographic resolution of the data require that the data be aggregated geographically, which results in an ecologic study with inferences drawn at a group and not an individual-level. Typically, individual-level studies are considered to be methodologically stronger, but in this case individual-level inferences would be counter to the research goal, which is to create a model using readily available data in order to assist with pre-event mitigation and post-event response.

Factors that contribute to the variation in individual village death rates include the irregular shape of the village regions, the fact that distance was measured to the centroid of the village, the differences in building inventory and geologic substrate, and the effect of secondary hazards such as landslides. Despite these factors and differences in methodology, there is relative consistency with the vulnerability functions developed for fatalities. A simple spatial model will never be able to predict all of the local variation, but it can illustrate the general trends needed to make informed decisions regarding resource allocation.

Weakness and potential improvements to the model

The proposed model employs a simple vulnerability function that looks only at distance from the fault rupture. While the casualty modeling methodology based on maximum coseismic slip and distance is an improvement over methodologies currently being utilized in the public health community, it could be improved. Accounting for complexities of the fault rupture such as directionality of the rupture and anisotropy in the propagation of seismic waves could help to improve the accuracy of the model. However, for simple earthquakes on strike-slip faults or point earthquakes the maximum coseismic slip model may be similar to epicenter or surface rupture. In addition, the model can be improved by refining population estimates adding other relevant components such as construction and geologic variables.

Confounding

It is unlikely that there is confounding by demographic factors. Confounding requires an association between demographic variables such as age, gender, socio-economic status, disability or another risk predictor and the distance from the fault. In order for such individual-level factors to confound the relationship presented in this study it would require a large number of individuals with a particular demographic characteristic clustered within a village (or township). Preliminary analysis indicated that there were no significant associations between available individual-level factors, age, gender, and disability and the exposure, distance, in this earthquake. The propagation of seismic energy and location of a fault rupture is independent of demographic characteristics, so confounding by demographic factors is unlikely in this and other earthquakes.

Applicability and importance of the research and future research

Historically, in large events, especially in isolated or developing regions, the number of casualties has not been not known for days or even weeks. This has greatly hindered rescue and recovery efforts. Often initial estimates differ from actual casualties by an order of magnitude. The goal of the research is to develop a simple spatial model that can be used to quickly ascertain maps of likely casualties post-event and to model the distribution of casualties in likely events to assist in planning and mitigation. Studies of geographically aggregated outcomes are appropriate in achieving these objectives. Improvements can be made by increasing the accuracy and resolution of the input data. The global implementation of a simple casualty modeling methodology in conjunction with a real-time information dissemination system can supply important information in a timely manner, which will reduce the lives lost in future earthquakes.

The Chi-Chi earthquake is an example of a complex fault rupture than is not easily characterized by simple spatial models. A large portion of the world prone to seismic events has similar faulting structures as the Chelungpu fault. The distance-decay method using maximum coseismic slip is a framework that is applicable to both simple and complex fault ruptures. Further research is needed to refine the relationships and create universally applicable vulnerability functions. The spatial location of fatalities and injuries must be captured in post-event epidemiologic analysis in order to increase the accuracy and utility of spatial models. The maximum coseismic slip framework will allow for a single set of vulnerability functions to be used in creating risk maps for a given event. This method makes distinguishing between sides of the fault and the type of rupture unnecessary. Building damage curves based on the maximum coseismic slip framework will allow for a simple method to estimate the spatial distribution of earthquake-related casualties for any type of fault rupture.

CHAPTER 4 : DEVELOPMENT OF A PREDICTIVE SPATIAL MODEL FOR CASUALTIES SUSTAINED DURING THE CHI-CHI EARTHQUAKE

4.1 Introduction

The importance of the problem

The spatial distribution of casualties in earthquakes has not been well quantified, despite its enormous importance to emergency planning and disaster relief efforts. Spatial knowledge is paramount in urban search and rescue, the location of critical communications, and the storage and distribution of food, medical, and water supplies. The probability of survival of victims trapped in an earthquake goes down rapidly as time of entrapment increases. The ability to rapidly model the likely spatial distribution of death and injury immediately post-event would allow for better allocation of scarce resources and appropriate prioritization rescue supplies, which could lead to a reduction in the number of lives lost as well as the seriousness of injuries. The Chi-Chi earthquake presents a unique opportunity to analyze the spatial patterns of earthquake casualty due to the availability of high quality seismic, building collapse, death, and injury data with geographic identifiers.

Issues with existing modeling techniques

The Chi-Chi earthquake occurred on an inclined thrust fault. The earthquake resulted in a 100 km surface rupture west of the epicenter location. The geology and faulting structures of the region are illustrated in Figure 4-1. The rupture resulted in an asymmetry in ground motion between the hanging wall (eastern) and footwall (western) sides of the fault. This asymmetry in ground motion and consequently in damage and casualties limits the applicability of simple spatial models commonly used in public health, such as concentric circles radiating outward from the epicenter, to complex ruptures similar to Chi-Chi.

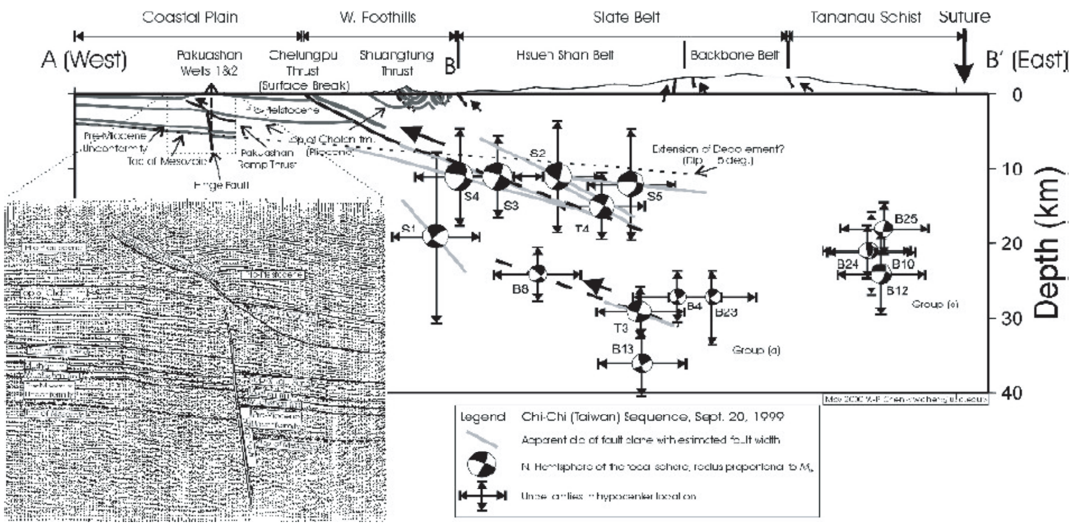


Figure 4-1: Diagram of the Chi-Chi Rupture Sequence, taken from Kao and Chen, 2000

This difficulty is noted by Pai in their study of near fault mortality in the Chi-Chi earthquake. On average mortality was 3 times greater on the hanging wall side of the fault, but they were unable to account for this trend and simultaneously develop a simple relationship between mortality and distance to the fault (Pai, 2004). A simple casualty vulnerability relationship is necessary in order to develop a predictive spatial model immediately post-event prior to all of the seismic and damage data being available. However, if a vulnerability function similar to the one developed by Pai is applied to future casualty models for similar faulting structures the risk could be substantially underestimated for the hanging wall side of the fault and overestimated for the footwall side. In order to have utility in the public health and emergency management community spatial models must be straightforward enough to rapidly estimate the casualties by those without an extensive background in faulting structures.

Goal of the Analysis

The high quality of casualty data in the Chi-Chi earthquake allows for the development of a spatial model for both fatalities and injuries with data at different geographic resolutions. This extends the work in Sullivan (2008a) by extending the distance-based decay model centered on the maximum coseismic slip to the 1999 Chi-Chi event in several ways. First, the strengths and weaknesses of the coseismic slip methodology are further evaluated, including assessment of any patterns of over or under prediction; second, additional predictive variables are incorporated into the model, including construction class. In addition geologic data, including landslide susceptibility and geologic substrate, were evaluated. The result is the development of construction class specific fatality vulnerability functions. An injury vulnerability function and risk map are also developed, but there are no additional predictive variables due to lack of construction class data. These functions when coupled with data from past and future events will be critical in improving earthquake loss modeling.

Non-vertical (dipping) faults predominate in earthquake prone urban areas such as Los Angeles, Japan, Central and South America, Turkey, Iran, and Pakistan. Advances have been made in the ability to characterize faulting structures and simulate ground motions associated with earthquake scenarios. However, similar advances have not been made in the area of casualty modeling. A spatial model of casualties associated with complex faulting structures is a necessary step in bridging the divide.

4.2 Methodology

4.2.1 Casualty Data

Casualty data was obtained by request from the National Fire Agency of Taiwan. These data included counts of fatalities, injuries, missing, rescued, and partially and totally collapsed buildings for all townships that sustained earthquake damage. Counted injuries were those treated at a medical facility, but no measure of severity was obtained. There are no published studies or government statistics of individual-level injury epidemiology in the Chi-Chi earthquake. However, one source estimated that 90 percent of injuries were head injuries, open wounds, or fractures (Chen, 2003).

Damage statistics were acquired for 124 of the 359 townships in Taiwan. Townships were included in this analysis if data were available and they sustained any earthquake-related damage to property or people. The township level summary statistics are shown in Table 4-1 below.

Table 4-1: Summary of Township-level Casualty Statistics for the 124 Townships Damaged in the Chi-Chi Earthquake

	Overall Total	Average	St Dev
Population	9,281,900	83,621	88,129
People Rescued	5,004	41	114
People Injured	11,287	93	315
People Dead	2,499	21	53
Buildings Totally Collapsed	26,852	222	628
Houses Totally Collapsed	61,241	506	1,241
Buildings Partially Collapsed	24,494	202	720

4.2.2 Ground Motion and Geologic Data and Assumptions

Ground motion records were obtained from the Taiwanese National Weather Bureau. Taiwan has one of the best strong motion networks in the world including 708 free-field strong motion data sites. Each station has triaxial accelerometers, a digital recorder and a timing system (Liu, 1999). The strong-motion sites are spaced approximately 5 km apart, except in the Central Mountain Range where there are significantly fewer stations. They are positioned to capture ground motion in the nine metropolitan regions in Taiwan, near active fault zones, at a variety of geologic sites, and near important infrastructure like industrial sites and nuclear power plants (Lee, 2005). The distribution of strong-motion stations in Taiwan is shown in Figure 4-2.

Distribution of Taiwan's Strong Motion Stations

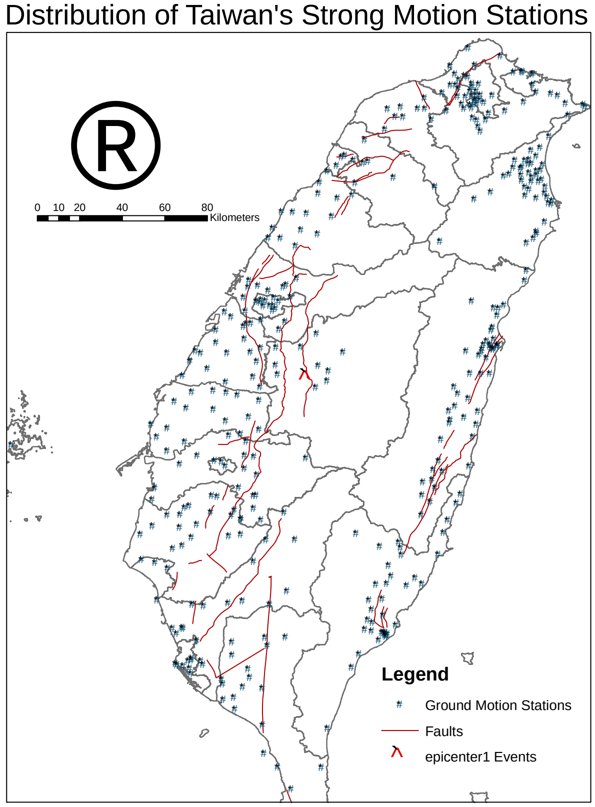


Figure 4-2: Distribution of Strong-Motion Stations in Taiwan

Ground motion is significantly affected by the type of geologic substrate. Local geologic conditions cause amplifications of different periods in the response spectra (Seed, 1976). If the period of the amplified ground motion is close to the natural period of a structure more severe building damage and subsequently more casualties can result. Therefore, a geotechnical classification map was employed. The classification scheme was developed by Risk Management Solutions, Inc. using digital geologic databases based on 1:250,000 resolution maps for soil type, liquefaction, and landslide (1998). The soil classification is a decimal system from 1 to 4 as follows; 1-hard rock, 2-gravel to weak rock, 3-stiff clay and sandy soil, 4-soft soil and artificial fill. A map of the soil distribution for Taiwan is shown in Figure 4-3. The area affected by the Chi-Chi earthquake contained no areas of particularly soft soil or artificial fill. Geologic substrate was not explicitly considered as the risk of liquefaction leading to casualties is low.

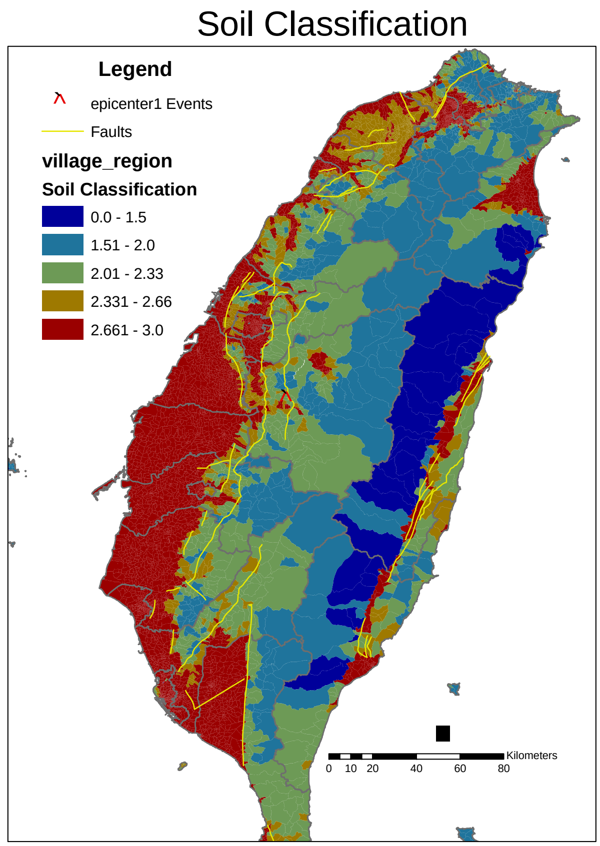


Figure 4-3: Map of Soil Classification for Taiwan

Data on landslide susceptibility was obtained on a township scale using the Risk Management Solutions, Inc. methodology (1998). The landslide risk in concentrated in the mountainous areas of central Taiwan. The Chi-Chi earthquake triggered approximately 10,000 landslides in the mountainous areas east of the Chelungpu fault. Three of the landslides resulted in fatalities.

4.2.3 Construction Class Data

Building collapse was the most significant cause of morbidity and mortality in the Chi-Chi earthquake accounting for roughly 90 percent of the earthquake-related fatalities (Tien, 2002). There are several published reports of the relationship between building attributes and mortality. Using these reports we abstracted the building class of buildings in which fatalities occurred. Additional information regarding fatalities in high-rise collapse, landslides, and building inventories was extracted through government and event reports (Tien, 2002; Lee, 2002). These data allowed us to link fatalities with the specific construction classes in which they occurred. The cause of death was unknown for 131 deaths and 140 deaths were non-building related, therefore these deaths were omitted from the construction class specific analysis. The data were mapped using Arcview 9.1 (ESRI, 2004). The importance of stratifying by construction class was evaluated by doing a score-like test and effect modification by construction class was evaluated using an interaction term approach in SAS v9.1.

4.2.4 Population Distribution Assumptions

Taiwan has a total of 359 townships with a mean population of 61,445 and a range of 1,723 to 529,025. The majority of townships have populations under 20,000 and the mean is heavily influenced by a small number of townships in large cities such as Taipei. The summary statistics concerning the population for all townships affected by the 1999 Chi-Chi earthquake are in Table 4-2. All analyses were at the township-level as injury data and construction class specific fatality data were available only at that geographic scale.

Table 4-2: Summary Statistics for Townships Affected by the Chi-Chi Earthquake

	Area (km2)	Population	Households	Deaths	Injuries
Average	135	87,681	25,820	20	92
St Dev	200	89,750	28,728	52	312

The Chi-Chi earthquake occurred at 1:47 am, while most people were sleeping. 2000 Census data, which is residential, is appropriate for this earthquake. Building inventory estimates for each township were made using assessed residential building value data by construction type for that township. The assessed value was used instead of building count, because value is a better proxy than number for the number of occupants in a particular construction type. Buildings with high values tend to be multi-family and therefore have more residents. The building inventory data were at a township level. Occupancy and construction type tends to be consistent on a small geographic scale, but can vary substantially in larger geographic regions. Assessed value statistics are published by township.

To estimate the number of people at risk at the time of the earthquake in each building class in each township, the population count from the 2000 census was multiplied by the percentage of a particular construction class, based on assessed values, in that township. In effect, we are assuming that the population was distributed in proportion to the assessed value for each construction class.

4.2.5 Seismic Model and Assumptions

The vulnerability functions are distance-based and assume a decay relationship around the 100km rupture. Seismologists have demonstrated that simple exponential models can be used to characterize the loss of seismic energy as waves propagate outwards from the epicenter (Howell and Shultz, 1975). The overwhelming majority of the casualties in earthquake are related to building collapse and building collapse is highly correlated to ground-shaking, therefore it follows that casualty distribution should also demonstrate decay with distance. Figure 4-4 shows the axial variation model centered on the area of maximum coseismic slip for the length of the surface rupture and the distribution of fatalities and injuries sustained during the Chi-Chi earthquake.

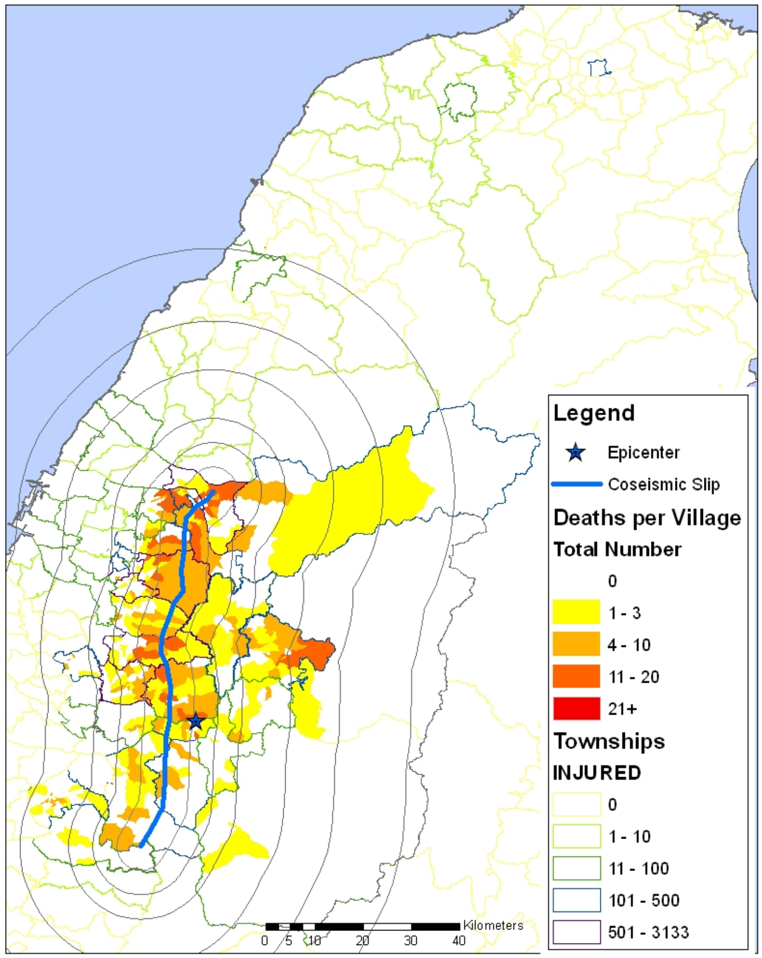


Figure 4-4: Axial Variation Model Centered on the Maximum Coseismic Slip for the Chi-Chi Earthquake

The line of maximum coseismic slip was drawn in ArcGIS 9.1 using data from Johnson and Segall (2004). The distance between the line of maximum coseismic slip and the centroid of each township and was calculated using ArcGIS 9.1.

4.2.6 Casualty Vulnerability Functions

The probability of death by building type for each township was modeled by the distance from the centroid of the region to the maximum coseismic slip stratified by construction class. A logistic model was fit using a generalized estimating equation approach to the number of casualties and population for each construction class in each township. The form of the model is:

Logit $(P(Y_{ic}=1 | x_i)) = A_{ic} + B_{ic} * x_{i.}$ where, Y_i is the number of deaths, x_i is distance from the centroids of township i, and the subscript “c” indicates construction class c. A vulnerability function was obtained from the coefficients A and B. A is the intercept term corresponding to the fatality measure at a distance of 0 km from the area of maximum coseismic slip and B is a measure of the decay of fatalities by distance.

Clustering by township was accounted for with the generalized estimating equation approach, exchangeable correlation structure and use of robust variance estimation. The data were then analyzed in SAS version 8.2. To obtain the fatality vulnerability functions, parameters were estimated for separately for the 5 construction classes: mudbrick, masonry, reinforced concrete low-rise (RC Low), reinforced concrete high-rise (RC High), and other. Model fit was assessed by comparing the correlation between observed and predicted fatality counts for each township using Spearman correlations and plots. The expected counts were calculated by multiplying the population at risk in each area by the probabilities predicted by the model.

To further assess model fit a fatality risk map was created by determining the distance between the centroid of each *village* and the maximum coseismic slip using

ArcGIS 9.1. The map was created at a village-level because that is the smallest geographic unit where there were casualty data available. Even though the vulnerability functions were developed at the township-level, we assessed the model's ability to predict casualties at the village-level since the improved geographic resolution should make it more useful to local emergency responders. The injury risk map employed similar methodology except that all injury data were on a township level.

4.3 Results

4.3.1 Fatality Vulnerability Functions

As shown in Table 4-3 the relative magnitude of the casualty rates between building classes is within the range of what would be expected from previous earthquakes and laboratory experiments. The significance of stratification by construction class was demonstrated by an interaction term approach and a score-like test. Effect modification was present as all the interaction terms for the 5 construction classes were significant at the 0.1 level and all the interaction terms except high-rise reinforced concrete were significant at the .05 level. The score-like test yielded a p-value of <.0001 indicating that the model that accounts for construction class fits better than the model that included distance only. Mudbrick buildings have much higher death rates than any of the other building classes. Both concrete and masonry buildings that have been seismically reinforced performed similarly and a deal better than the unreinforced masonry buildings. The "other" category is difficult to characterize generally, because it includes multiple construction types including steel and buildings of mixed construction. Table 4-3 is a summary of the data from the 45 townships used in the construction class specific model.

Table 4-3: Summary Statistics for the Townships used to Model the Construction Class Specific Vulnerability Functions

	Average Death Rate	Death Rate Stdev	Townships containing CC	Total Pop in CC
Mudbrick	**0.54%**	**0.91%**	**35**	**215,561**
Masonry	**0.06%**	**0.12%**	**45**	**948,852**
RC Low	**0.10%**	**0.37%**	**45**	**1,464,687**
RC High	**0.19%**	**0.54%**	**27**	**365,373**
Other	**0.13%**	**0.18%**	**45**	**189,070**

The construction class specific vulnerability functions obtained for the Chi-Chi earthquake using an axial variation model centered on coseismic slip are shown in Table 4-4 and illustrated in Figure 4-5. There is a clear distance-decay relationship with all the construction classes. The modeled proportional risk of death decreases approximately 13% per km shift away from the line of maximum coseismic slip for mudbrick, low-rise reinforced concrete, and other. For Masonry and high-rise reinforced concrete the modeled proportional risk decreases at a rate of roughly 8-9% per km shift away from the line of maximum coseismic slip.

Table 4-4: Construction Class Specific Results from the Regression Analyses for Fatalities

	Intercept (95% CI)	Coefficient (95% CI)	Spearman ρ
Mudbrick	1.36% (0.67%, 2.77%)	-0.134 (-0.22, -0.04)	0.754
Masonry	0.10% (0.04%, 0.25%)	-0.084 (-0.18, 0.01)	0.502
RC Low	0.10% (0.02%, 0.38%)	-0.137 (-0.33, 0.06)	0.429
RC High	0.21% (0.03%, 1.27%)	-0.092 (-0.22, 0.04)	0.263
Other	0.13% (0.06%, 0.26%)	-0.128 (-0.21, -0.047)	0.523

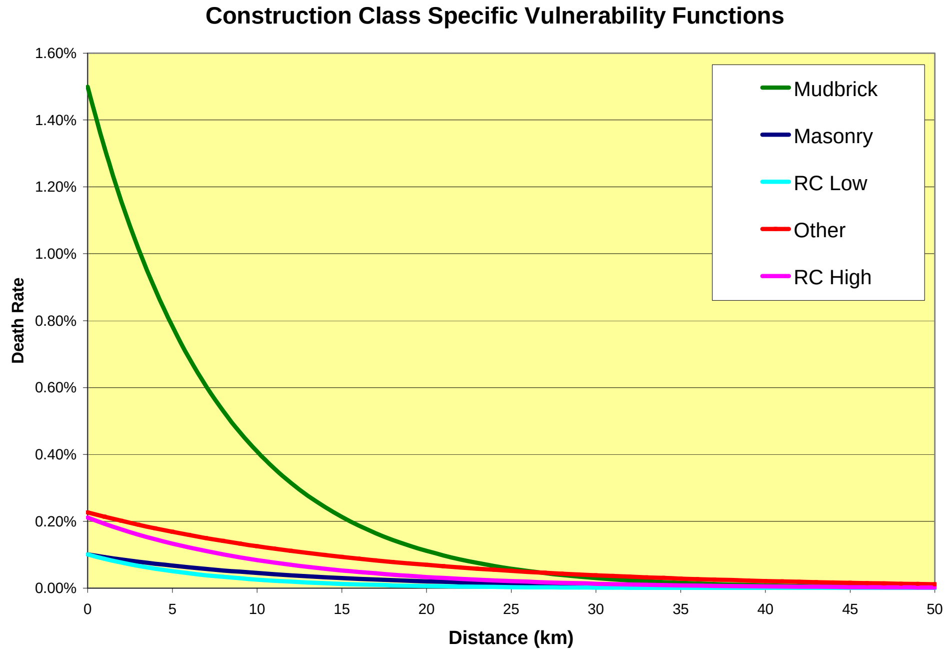


Figure 4-5: Construction Class Specific Vulnerability Functions for the Chi-Chi Earthquake

4.3.2 Fatality Risk Map

The construction class specific vulnerability functions, which were developed at township-level, were applied to village-level population, building inventory, and distance data in order to predict casualties and create a risk map for the Chi-Chi earthquake, as part of further evaluation of the axial variation model centered on coseismic slip. Figure 4-6 and Figure 4-7 show the map of actual mortality and modeled mortality sustained in the Chi-Chi earthquake respectively. The model includes only near fault mortality and the deaths sustained as a result of the high-rise collapses in Taipei were not captured. The model predicts 1820 fatalities compared to 2360 fatalities sustained during the Chi-Chi earthquake.

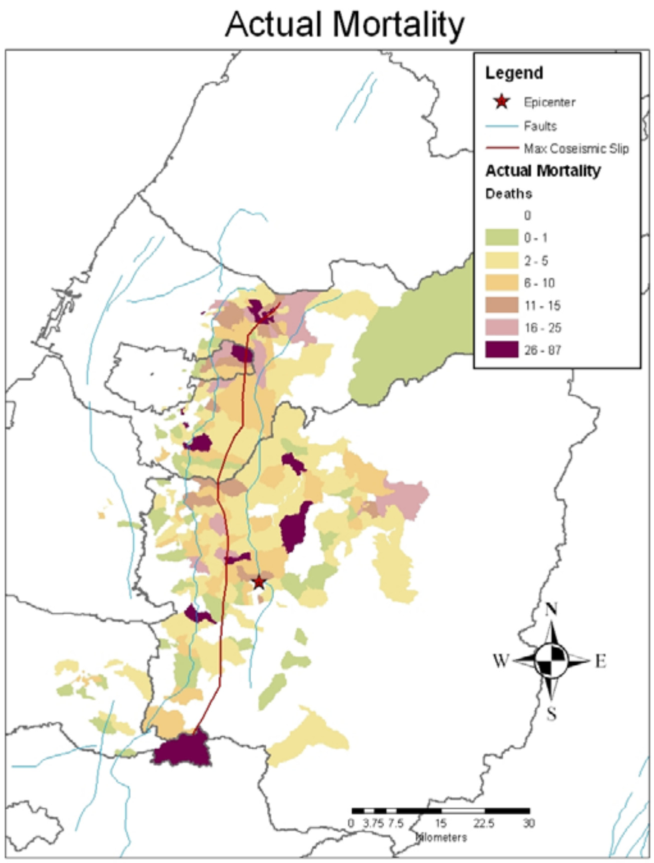


Figure 4-6: Map of Actual Mortality Sustained in the Chi-Chi Earthquake, Actual Deaths=2360

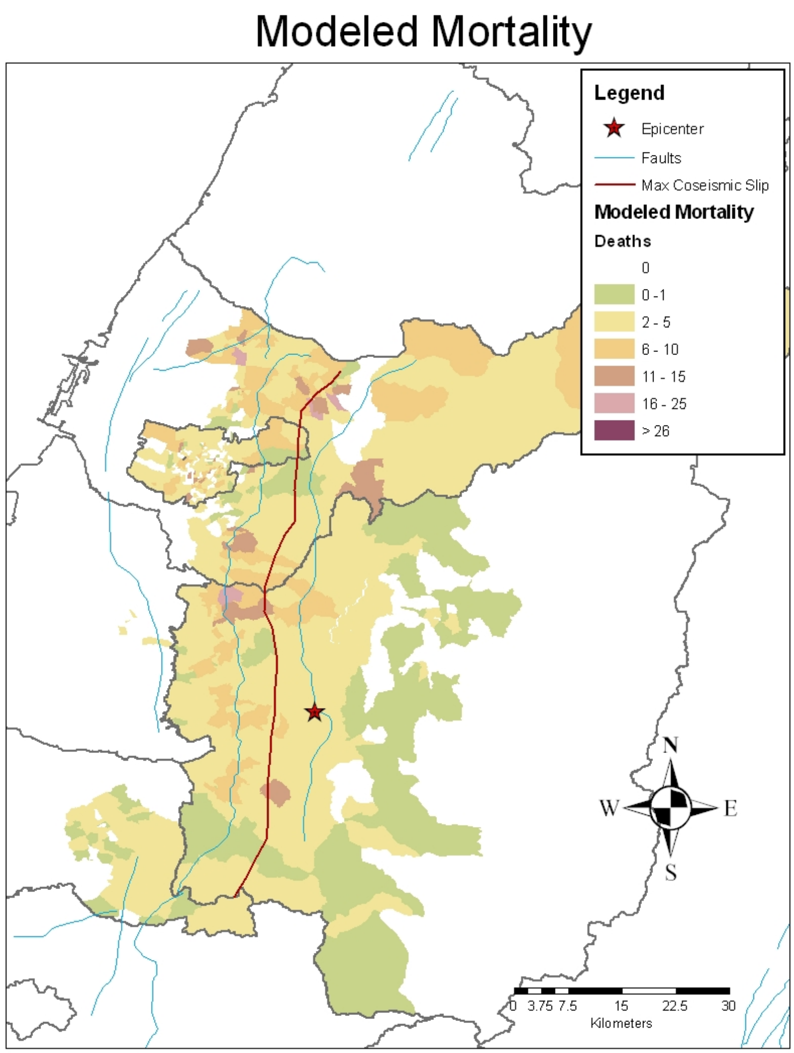


Figure 4-7: Map of Modeled Mortality Sustained in the Chi-Chi Earthquake, Modeled Deaths=1820, Near Fault Only

Although, population and distance were entered into the model at a village-level the inventory data were only available at the township level. This required the assumption that building inventory was uniform throughout all villages in a township and results in a smoothed representation of the event. Comparison of Figures 24 and 25, show that the model fails to predict the concentration of fatalities about 35 km northeast of the epicenter. These were sustained as a result of a landslide, but landslide risk was not explicitly modeled. Table 4-5 shows the actual and modeled fatalities, summed over all villages, by construction class.

Table 4-5: Comparison of Actual versus Modeled Fatalities by Construction Class

Building Class	Actual Fatalities	Modeled Fatalities
Mudbrick	962	913
Masonry	383	325
Low-rise RC	363	247
High-rise RC ***	411	82
Other Building	224	251
Landslide *	107	NA
Non Building *	42	NA
*** Majority of high rise collapse fatalities were due to long period ground motion in Taipei and are not captured in near fault modeling * Model only accounts for building related fatalities		

4.3.3 Injury Vulnerability Function

The estimated, distance-based vulnerability function for injuries in the Chi-Chi earthquake is shown in Figure 4-8. The Tungshih Township had an injury rate of 5.4% and that data point was included in all analyses (including fit statistics), but is omitted from Figure 4-8 for clarity. The model only accounts for injuries that were seen in hospitals. The vulnerability function (developed in Sullivan, 2008a) was applied to population and distance data in order to create a spatial model of injuries sustained during the earthquake.

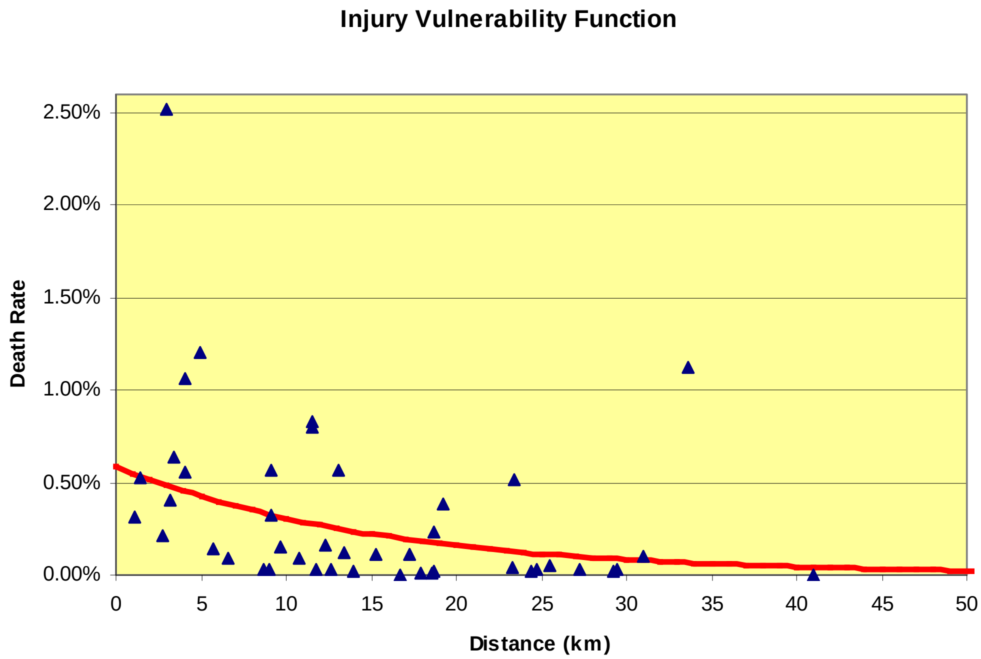


Figure 4-8: Injury Vulnerability Function for the Chi-Chi Earthquake

4.3.4 Injury Risk Map

The injury model is not construction class specific as no data on construction type and injury were collected. The vulnerability function is used to create a risk map in order to evaluate the strengths and weaknesses of the methodology. All injury data and modeling were at the township-level. The utility of the injury model is in properly locating and allocating medical supplies as well as in targeting search and rescue resources. Although, finer geographic resolution would be preferred medical and search and rescues resources are often coordinated at a township or county-level. The actual distribution of medically treated injuries and modeled results are shown in Figure 4-9 and

Figure 4-10. The number of modeled injuries sustained during the earthquake is 11,059 and the actual number of injuries sustained during the earthquake is 11,287.

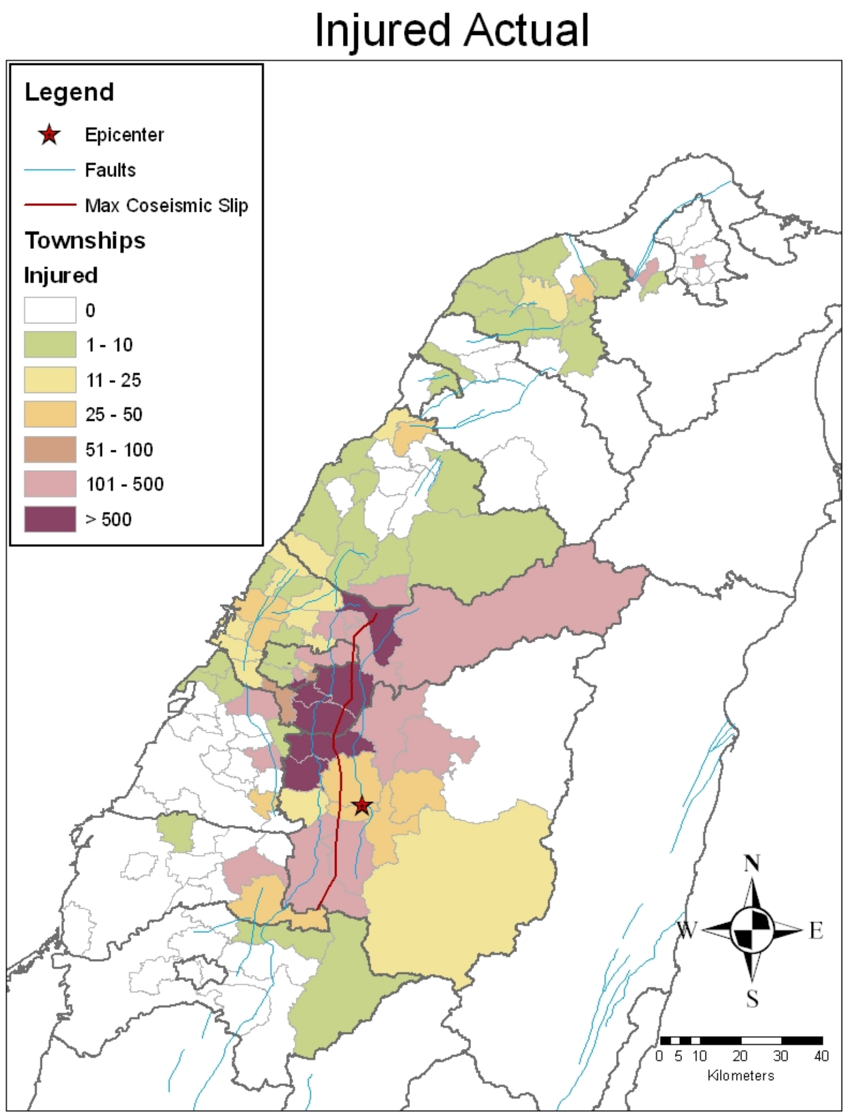


Figure 4-9: Map of Actual Morbidity Sustained in the Chi-Chi Earthquake, Actual Medically Treated Injuries=11287

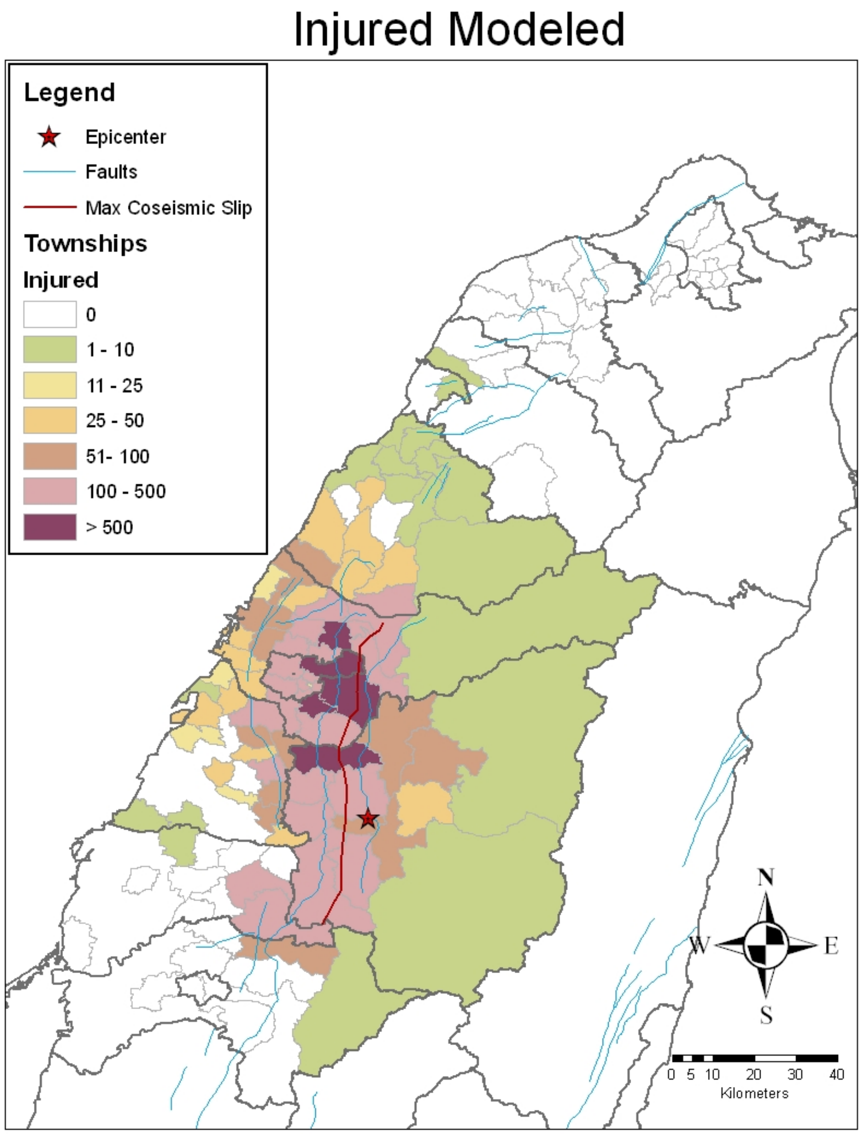


Figure 4-10: Map of Modeled Morbidity Sustained in the Chi-Chi Earthquake, Modeled Hospitalized Injuries=11119

The axial variation model does not account for the directionality of the surface rupture. In the case of the Chi-Chi earthquake the rupture was south to north and the majority of the seismic energy propagated in the northerly direction.

4.4 Discussion

Summary of Key Results

The work in Sullivan (2008a) provides a framework through which to get estimates of the distribution and magnitude of injuries and fatalities immediately post-earthquake. This work is extended in this analysis by demonstrating that by using construction class, population, and seismic data risk maps can provide a useful estimation of near-fault mortality. We performed a score-like test and likelihood ratio test comparing the fit of the models with and without the addition of construction class and confirmed with a highly significant result that the model fit is better with the addition of construction class. The heterogeneity of the parameters between construction classes illustrates the importance of stratifying by construction class when modeling future events. More widely applicable casualty vulnerability functions could be created by coupling construction class specific data from the data from this earthquake with data from other historical events. Provided there is overlap in construction class these functions could be used to create earthquake casualty risk maps for seismic areas throughout the world. Although, the models could have utility in public health planning they do an inadequate job of predicting casualties that are not near the fault.

Strengths and Weaknesses

If real time ground motion data were available at every site it would eliminate the need to model casualties based on faulting structure. However, tri-axial accelerometers are expensive and typically only found in developed countries in areas known to be seismically active. In addition, in order to use ground motion data the event has to have already occurred, therefore a modeling methodology based on faulting structures or modeled ground motion is necessary for pre-event mitigation.

A casualty modeling methodology based on maximum coseismic slip and distance is an improvement over methodologies currently being utilized in the public health community, however, it could be improved. Accounting for complexities of the fault rupture such as directionality of the rupture and anisotropy in the propagation of seismic waves would help to improve the accuracy of the model. In the Chi-Chi earthquake it was not necessary to take into account geologic substrate because of the uniformity of the geologic conditions, but in other earthquakes this may not be the case. In locations with soft soil or prone to liquefaction the geology of the region should be evaluated in developing the distance-based vulnerability functions. The vulnerability functions would theoretically need to be stratified on geologic site conditions or soil classification, in addition to construction class. Also, the model fails to account for deaths by landslide. In the future building casualty models should be coupled with casualty functions derived from landslide prediction models in order to more accurately predict all earthquake-related casualties.

Assumptions for the distribution of the population affected by the Chi-Chi earthquake were relatively easy straightforward, because the earthquake occurred while the population was sleeping. Therefore residential population estimates, like census data, were an accurate depiction of the distribution of the population at the time of the earthquake. This would not be the case during the day or at commute times. The location and distribution of the population by construction class will be different at different times of day. In areas like California where the commercial inventory is constructed of less seismically sound materials than the residential building inventory this would lead to notably different casualty estimates depending on the time of day. Data on commercial inventories and census data on the commuting population are usually available, but users must be cognizant that they are making estimates using the correct population distribution and inventory. When creating maps for use in pre-event mitigation it would be helpful to run the same event at different times of day in order to understand the influence of time of day.

The predictive ability of the model could be improved most dramatically by having a more detailed building inventory. More specific construction class information including Applied Technology Council (ATC) class, seismic retrofits, information about soft stories, and building age would greatly improve casualty estimates. Typically, construction class data are only available at a large geographic scale, such as city or county. Better geographic resolution of the construction class data would help to improve the model.

This analysis illustrates one of the issues with modeling engineered high-rise structures. A total of 411 deaths occurred in high-rise structures, but only 16 high-rise buildings collapsed (Tien, 2002). This is a small number when compared to the nearly 175,000 buildings and houses that partially or totally collapsed during the Chi-Chi earthquake. High-rise buildings must follow strict seismic codes so collapse is a low probability, high consequence event. Proper construction and maintenance is critical in preventing large loss of life. High-rise structures are more likely to collapse because of long period ground motion or ground motion amplification, which often occurs a long distance from the fault. A distance-based method reasonably represents near fault mortality, but may not adequately capture mortality away from the fault, which is most likely to be in high-rise structures. Due to the low probability and high consequences of the collapse of engineered structures there is no easy method for developing spatial models or vulnerability functions for high-rise collapse.

The collapse mechanisms are varied and complex and there can be a variety of causes including open space problems, column failure of the lower stories, and construction quality. The issues with high-rise construction are often not known until a seismic event occurs. In addition, the spatial pattern of high-rise collapse is not similar to the other building classes. Eighty-seven of the fatalities occurred 150km away from the epicenter and 100km away from the maximum coseismic slip. Distance-based modeling techniques would not predict fatalities at this distance.

High-rise structures tend to be concentrated in dense urban areas giving a limited sample size at various distances from the fault. This coupled with the small number of collapses in any given event means that inferences must be based on extremely small sample sizes. High rise buildings typically are more affected long period ground motions, which can travel significantly longer distances than short period ground motions. Distance-based models are not the most effective means for modeling casualties in high rise collapse because collapse can occur at significant distances from the rupture, especially when geographic features lead to the amplification of long period ground motions. For the purpose of this analysis an essentially uniform vulnerability function was used as shown in Figure 4-5, so the casualties sustained as a result of high rise collapse in Taipei were inadequately captured by the model. More research is needed to be able to better understand and model casualties sustained as a result of high-rise collapse. A model based on spectral displacement or another instrumental ground motion measure that can quantify the variations between individual buildings is necessary to capture patterns of high rise collapse, but would be significantly more complex and require more data than a distance-based model.

The limitations in the geographic resolution of the data require that the data are aggregated geographically, which results in an ecologic study with inferences drawn at a group and not an individual-level. Typically, individual-level studies are considered to be methodologically stronger, but in this case individual-level inferences would be counter to the research goal, which is to create a model using readily available data in order to assist with pre-event mitigation and post-event response. To fulfill this goal the model inputs need to be easily attainable and relatively universal. Population, basic construction, and geologic data at an aggregate level meet the criteria.

Confounding

Geographic and structural factors are significantly more important than demographic factors. The overwhelming majority of earthquake casualties occur because of structural failure (Coburn, 1992). In the Chi-Chi earthquake 90 percent of fatalities can be directly attributed to building collapse. It is unlikely that there is confounding by demographic factors. Confounding requires an association between demographic variables such as age, gender, socio-economic status, disability or another risk predictor and the distance from the fault. In order for such individual-level factors to confound the relationship presented in this study it would require a meaningful association of a particular characteristic to be associated with characteristics of the earthquake, in this study with distance. Preliminary analysis indicated that there were no significant associations between available individual-level factors, age, gender, and disability and the exposure, distance, in this earthquake. The propagation of seismic energy and location of a fault rupture is independent of demographic characteristics, so confounding by demographic factors is unlikely in this and other earthquakes.

Although the literature has shown an increased risk in the elderly and disabled in some earthquakes, it is probable that this is a result of building and geographic factors rather than a casual association. The increased fatality rate for the elderly and disabled may be attributed to the fact they often live in older or sub-standard housing. In the Kobe earthquake there was an increased risk of casualties among the elderly, but a disproportionate number of elderly people lived in traditional post-and-beam houses that were not seismically sound (Kunii, 1995). Chou (2004) did find that age and SES were associated with mortality following the Chi-Chi earthquake. However, they did not account for construction class, ground motion, or extent of building damage so that their result is not inconsistent with little or no confounding by factors such as age and SES, when interest centers on construction class and or ground motion.

Applicability and Importance of the Model

Historically, in large events, especially in isolated or developing regions, the number of casualties has not been not known for days or even weeks. This has greatly hindered rescue and recovery efforts. Often initial estimates differ from actual casualties by an order of magnitude. The difficulty is in balancing the simplicity and the accuracy in order to maximize the utility to emergency managers and the public health community. The accuracy of the model might be improved by accounting for more complex seismologic modeling and capturing more specific building inventory and population data. However, sizeable uncertainty and complexity is introduced with each additional parameter. The public health community might be best served by utilizing an easy to understand modeling framework that is applicable to all seismic events rather than a complex engineering framework.

This analysis proposes a framework through which to create casualty risk maps for seismic events. Future research and event data need to be analyzed to create vulnerability functions that are applicable for all sizes of events and construction classes. The framework can then be applied to create a set of functions or simple software program that can automatically create casualty risk maps for use by the public health community in preparedness planning and post-event response.

CHAPTER 5 : ASSOCIATION BETWEEN FATALITIES AND GROUND MOTION PARAMETERS IN THE CHI-CHI EARTHQUAKE

5.1 Introduction

Importance of the Problem

Effective response and recovery and earthquake hazard mitigation is dependent on real time assessment of earthquake effects. Correctly targeting emergency response after a large earthquake can be a difficult task. The ability to rapidly model the likely spatial distribution of death and injury immediately post-event would allow for better allocation of scarce resources and appropriate prioritization rescue supplies, which could lead to a reduction in the number of lives lost as well as the seriousness of injuries. In addition, targeted pre-event hazard mitigation is paramount in preventing earthquake morbidity and mortality. In order to have effective mitigation procedures we must first understand the likely magnitude and distribution of casualties, which can be achieved through accurate loss modeling.

Issues with Current with Modeling Techniques and Advantages of using Spectral Response

Good emergency management and response requires an understanding of the distribution of casualties. In order to rapidly model loss there must be a quantitative framework for understanding ground motions and their impact on structural failure and casualties. Historically, intensity scales such as the Modified Mercalli Intensity (MMI) scale have been used to quantify ground motions. However, MMI is a descriptive measure determined by damage and observation. For this reason inferences based on MMI are not generalizable and not available quickly for a rapid response. In addition, most developed areas of the world frequently affected by earthquakes now have strong-motion networks. Strong-motion networks are series of digital accelerographs that record peak ground acceleration (PGA). From these data the response spectra and peak ground velocity (PGV) can be calculated. Strong-motion data are quantitative measures based on recorded instrumental intensities.

Casualty relationships and algorithms developed from strong-motion data would be quantitative, independent, and generalizable to areas with different building inventories and geologic substrates. In addition, the engineering community uses spectral response data in analyzing performance of structures. A shift towards using spectral acceleration in earthquake casualty modeling allows for better and more accurate estimation of building response. It also increases the ability to use engineering research in casualty modeling without first having to translate into a descriptive measure such as MMI.

Goal of the Analysis

There is extensive research evaluating the relationship between ground motion and building response and documenting that an overwhelming majority of earthquake casualties occur as a result of building failure (e.g., Coburn, 1992; Glass, 1977; Osaki, 2001; Petal, 2004; Pomonis, 1992). However, the relationship between specific ground motion parameters and earthquake casualties has not been well quantified.

The large strong-motion network in Taiwan and quality of the casualty data gathered after the 1999 Chi-Chi earthquake creates a unique dataset from which to begin to quantify the relationship between ground motion parameters and casualties. This study focuses on several ground motion parameters that are commonly used in seismology and earthquake engineering to represent ground shaking intensity, and their association with fatalities. The parameters considered are Modified Mercalli Intensity (MMI), epicentral distance, peak ground acceleration (PGA), and spectral acceleration (SA) at several periods from 0.2 sec to 2.0 sec. The relationship between ground motion parameters and specific construction classes were also examined in order to begin to develop casualty rate vulnerability functions based on spectral acceleration. These findings are examined in light of the prevalent building types in the region and their dynamic response characteristics and compared to what would be expected from previous research on structural response to ground shaking.

5.2 Methodology

5.2.1 Casualty Data and Casualty Vulnerability Function Derivation

This study utilizes casualty data obtained by request from the National Fire Agency of Taiwan. These data included counts of fatalities, injuries, missing, rescued, and partially and totally collapsed buildings for each township that sustained earthquake damage. Counted injuries were those treated at a medical facility, but no measure of severity was obtained. There are no published studies or government statistics of individual-level injury epidemiology in the Chi-Chi earthquake. However, one source estimated that 90 percent of injuries were head injuries, open wounds, or fractures (Chen, 2003).

Damage statistics were acquired for 124 of the 359 townships in Taiwan. Townships were included if they sustained any earthquake-related damage to property or people. The township level measures are summarized in Table 5-1.

Table 5-1: Summary of Township-level Casualty Statistics for the 124 Townships Damaged in the Chi-Chi Earthquake

	Overall Total	Average	St Dev
Population	9,281,900	83,621	88,129
People Rescued	5,004	41	114
People Injured	11,287	93	315
People Dead	2,499	21	53
Buildings Totally Collapsed	26,852	222	628
Houses Totally Collapsed	61,241	506	1,241
Buildings Partially Collapsed	24,494	202	720

The majority of the fatalities were near fault, although there were several high-rise collapses causing substantial loss of life in Taipei 150 km north of the epicenter. Ninety percent of fatalities were within 25 km of the surface rupture and 75 percent were within 10 km of the surface rupture. A map of near fault mortality and building collapses are shown in Figure 5-1.

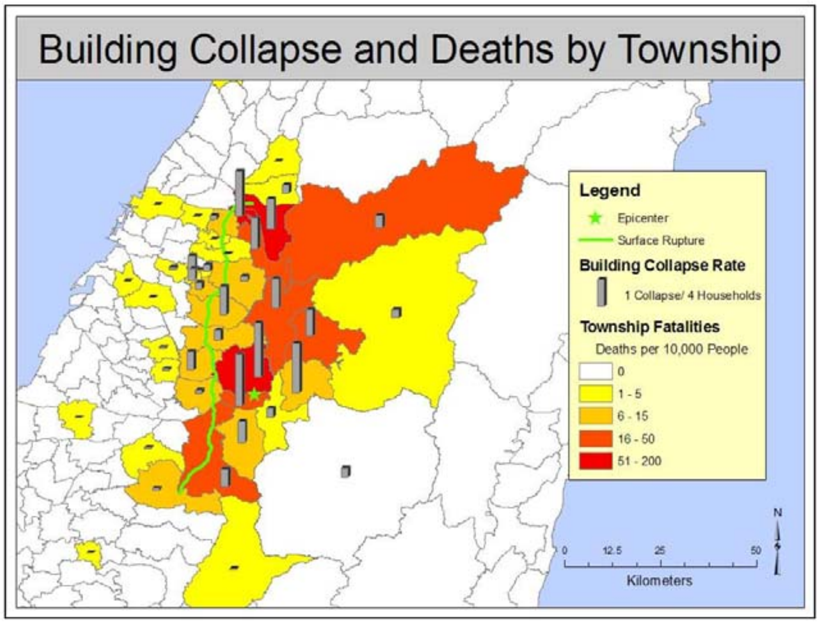


Figure 5-1: Map of near fault mortality and building collapse by township

5.2.2 Ground Motion Data and Processing of Ground Motion Records

Ground motion records (uncorrected acceleration time-series) were obtained from the Taiwan's Central Weather Bureau (CWB) web site: http://www.cwb.gov.tw/V5e/index.htm (last accessed: April 27, 2006). Taiwan has one of the largest strong-motion networks in the world including 708 free-field strong-motion data sites. Each station has triaxial accelerometers, a digital recorder and a timing system (Liu, 1999). The strong-motion sites are spaced approximately 5 km apart, except in the Central Mountain Range where there are significantly fewer stations. They are positioned to capture ground motion in the nine metropolitan regions in Taiwan, near active fault zones, at a variety of geologic sites, and near important infrastructure like industrial sites and nuclear power plants (Lee, 2005). The distribution of strong-motion stations in Taiwan is presented in Figure 5-2.

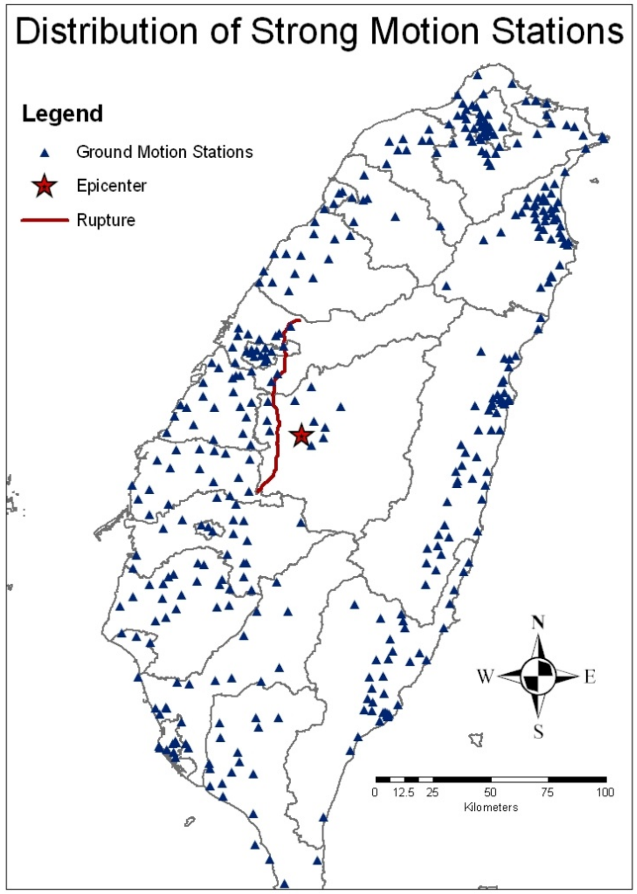


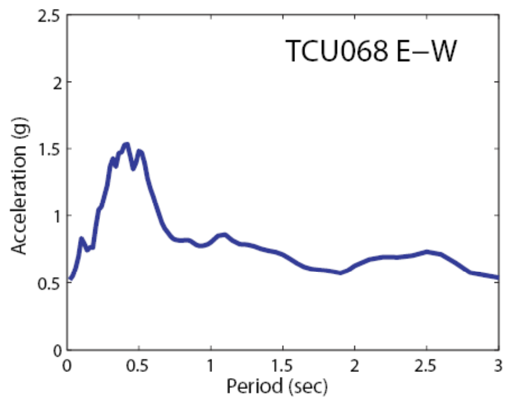
Figure 5-2: Distribution of strong-motion stations in Taiwan

More than 300 instruments were triggered during the 1999 Chi-Chi earthquake with epicentral distances ranging from 5 km to 200 km. Most recorded motions were on the foot-wall side of the fault since the hanging-wall side mainly falls in the Central Mountain Range (see Figure 5-2). Highest peak ground accelerations were in E-W direction (perpendicular to the N-S fault orientation) and reached nearly 1.0g.

The records were obtained from the CWB web site as uncorrected accelerograms. A baseline correction was applied by removing the mean from the record. It was observed that the displacements and some of the velocities obtained by integration of the

Chi-Chi accelerograms displayed significant drifts when removal of the mean alone was applied (Boore, 2001a; Wang, 2003), however the response spectra were not typically affected by the baseline correction (Boore, 2001a; Boore, 2001b). Response spectra for both E-W and N-S horizontal components were calculated using an algorithm developed by Nigam and Jennings (1969).

A total of 67 townships were included in the analysis. Ninety-five ground motion stations were contained within those 67 townships. Stations that were at ridge tops or had other special site or topographic effects (Lee, 2001) were excluded. After the removal of the stations with site specific effects there were a total of 13 townships that had more than one ground motion station. The station closest to the centroid of the township was used in the analysis. The duplicate stations were typically within a couple of kilometers of the station used in the analysis and the ground motion records differed slightly between stations. A correlation analysis was done for 4 townships with over 25 fatalities, where the duplicate ground motion records were not excluded for topographic effects. The Spearman correlation coefficient ranged between 0.67 and 0.77 for the 4 townships. Sample acceleration spectra for two stations that are near the high-casualty areas (TCU068 and TCU071) are presented in Figure 5-3. Note that TCU068 is on the hanging-wall side of the fault and displays unusually high spectral accelerations at long periods beyond 1s.



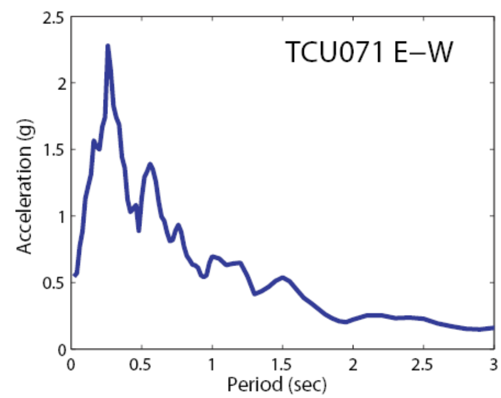


Figure 5-3: Sample acceleration response spectra

5.2.3 Building Inventory Data and Building Class Specific Analyses

A first step in developing a model for the effect of strong-motion on casualties modeling is to evaluate the relationships between building class specific ground motion and casualties. Casualty modeling relies on ground motion relationships being applicable at a regional geographic scale. In order to shift towards the use of ground motion measures obtained by instruments for casualty modeling we must first evaluate whether the patterns between building damage and ground motion developed for individual structures are similar to the patterns between casualties and ground motion stratified by building class at a regional geographic scale.

To further understand and assess the accuracy of using spectral response for earthquake casualty modeling, we evaluated the associations between casualties and ground motion stratified by building class. The number of fatalities by building class on a township-level was obtained from a publication by Tien. (2002). Figure 5-4, Figure 5-5, and Figure 5-6 present the number of deaths by building class and non-building causes of death, and the percentage of deaths by building class and non-building causes of death by township in Taichung and Nantou counties. The deaths in rural townships were primarily in mud-brick and masonry buildings. In urban townships the deaths occurred for the most part in 3-5 story reinforced concrete buildings with a soft story or high-rise reinforced concrete buildings (Tien, 2002).

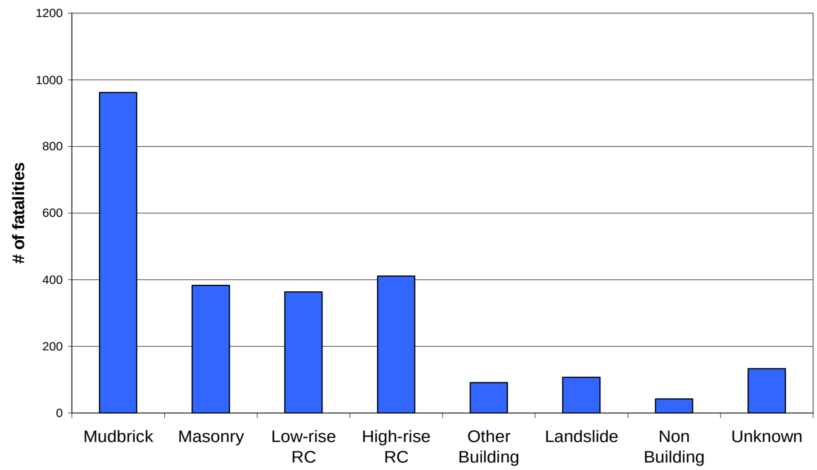


Figure 5-4: Number of Fatalities by Construction Class and Non-Building Causes of Death

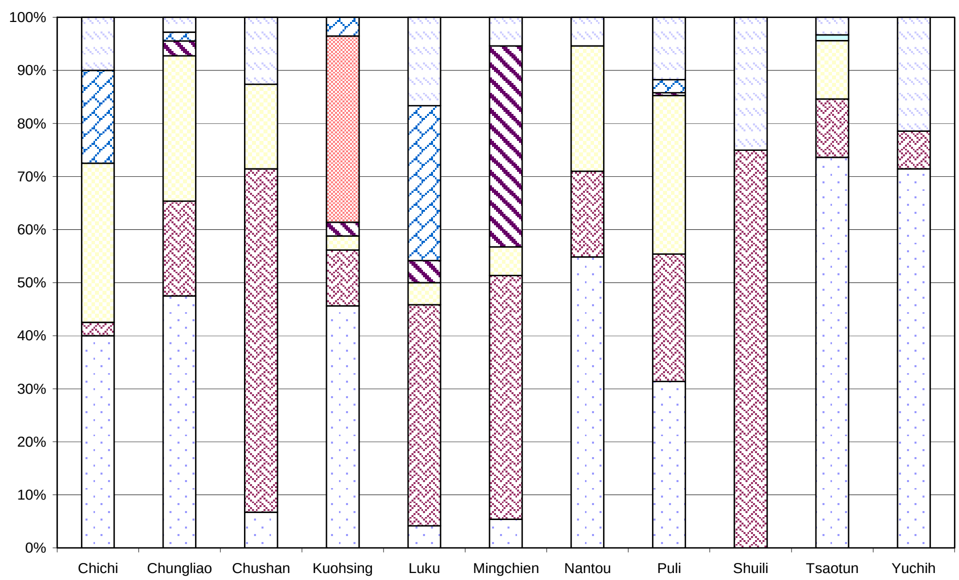


Figure 5-5: Percentage of Fatalities by Construction Class and Non-Building Causes of Death by Township in Nantou County (legend in Figure 5-6)

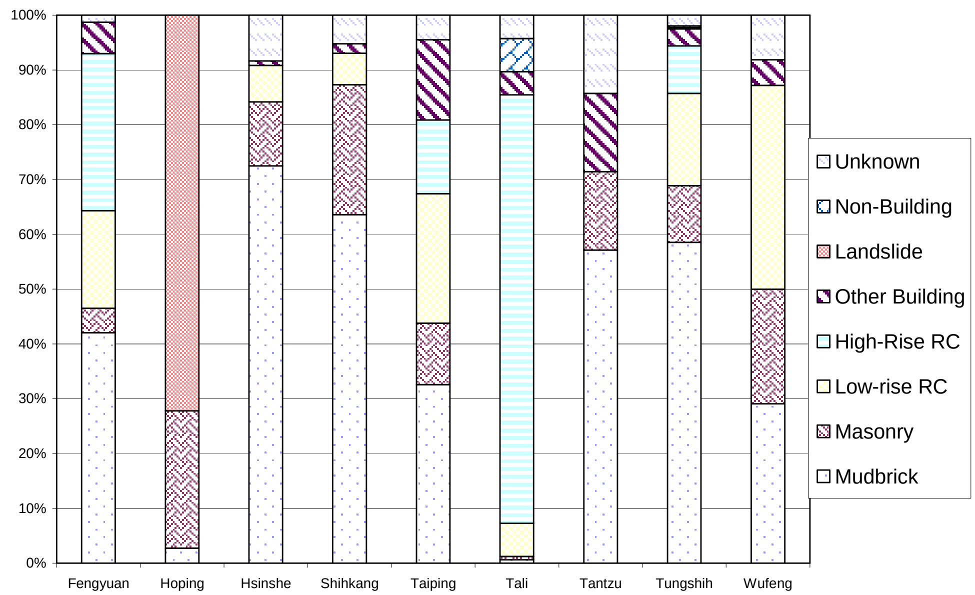


Figure 5-6 Percentage of Fatalities by Construction Class and Non-Building Causes of Death by Township in Taichung County

Building inventory estimates based on the monetary value of residential construction in a township were used in order to distribute the population by building class. The population at risk in the regression analysis was the number of people in the township multiplied by the percent of the specific construction type in the township. This ensured that both the term being modeled and the denominator were construction class specific. A perfect metric for assigning the population to a specific construction type is not available. However building value is a relatively good proxy for occupancy, because typically as the value of a residential structure increases, so do the number of occupants.

For each building type, casualties were plotted against SA at various periods. The probability of death by building type for each township was modeled by the SA, stratified by construction class. A logistic model was fit using a generalized estimating equation approach to the number of casualties and population for each construction class in each township. The form of the model is:

Logit $(P(Y_{ic}=1| x_i)) = A_{ic} + B_{ic}*x_{i.}$ where, Y_i is the number of deaths, x_i is measure of SA at a specific period, i, in g (9.8 (m/s^2)), and where models were construction class specific the subscript "c" indicates construction class c.

Clustering by township was accounted for with the generalized estimating equation approach with an exchangeable correlation structure and use of robust variance estimation. The data were analyzed in SAS version 8.2. To obtain the fatality vulnerability functions, parameters were estimated for separately for the 5 construction classes: mudbrick, masonry, reinforced concrete low-rise (RC Low), reinforced concrete high-rise (RC High), and other. Model fit was assessed by comparing the association between observed and predicted fatalities for each township using the Spearman correlations, p-values, and descriptively using plots.

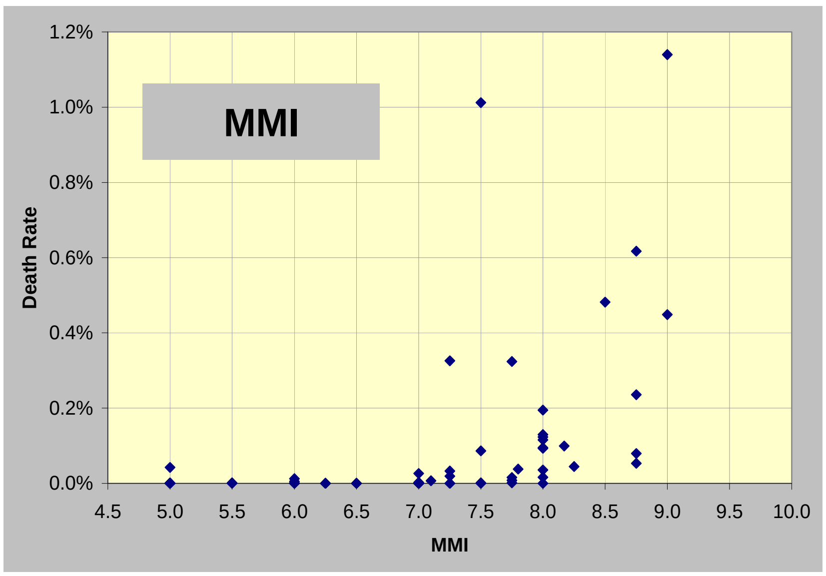
5.3 Results

5.3.1 MMI and Epicentral Distance

First the association between casualties and commonly used parameters such as MMI and epicentral distance were investigated (Figure 5-7). The Spearman correlation coefficient, shown in Table 5-2, for epicentral distance is 0.08 for deaths and 0.36 for injuries, with non-significant p-values. The complexity of the rupture limits the utility of this measure and the previous analyses address the reasons for this in detail (Sullivan, 2008a).

MMI better characterizes casualty relationships than epicentral distance. The Spearman correlation coefficient shown in Table 5-2 is 0.47 for deaths and 0.62 for injuries. This is expected as the definition of the MMI scale is damage dependent. The

MMI scale has no mathematical basis and uses a system of 12 roman numerals assigned on observed effects. It requires a qualitative assessment based on human observation, building response, and ground failure processes that can only be determined post-event by collecting observational data. Advancements in structural engineering have caused the scales to change over time and now a stronger ground motion may be required to reach a certain intensity than was required historically (Coburn, 1992).



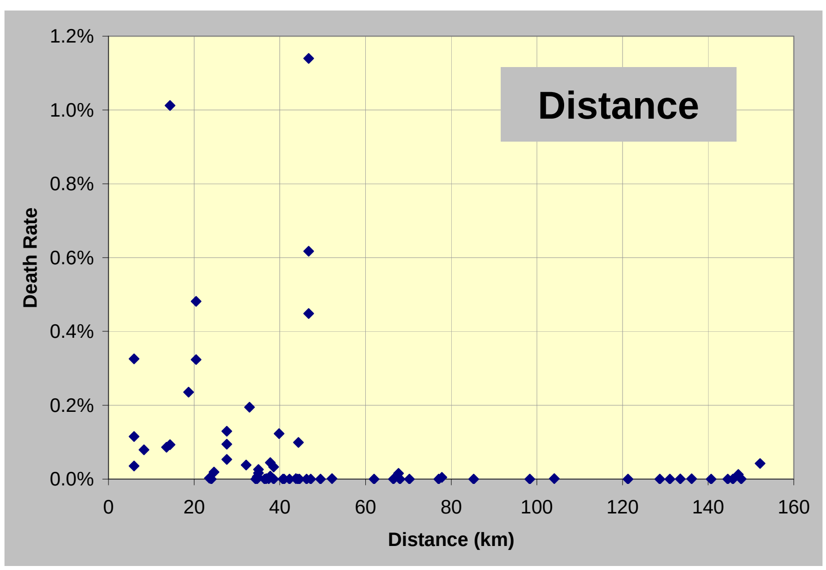


Figure 5-7: Death rates by MMI and epicentral distance

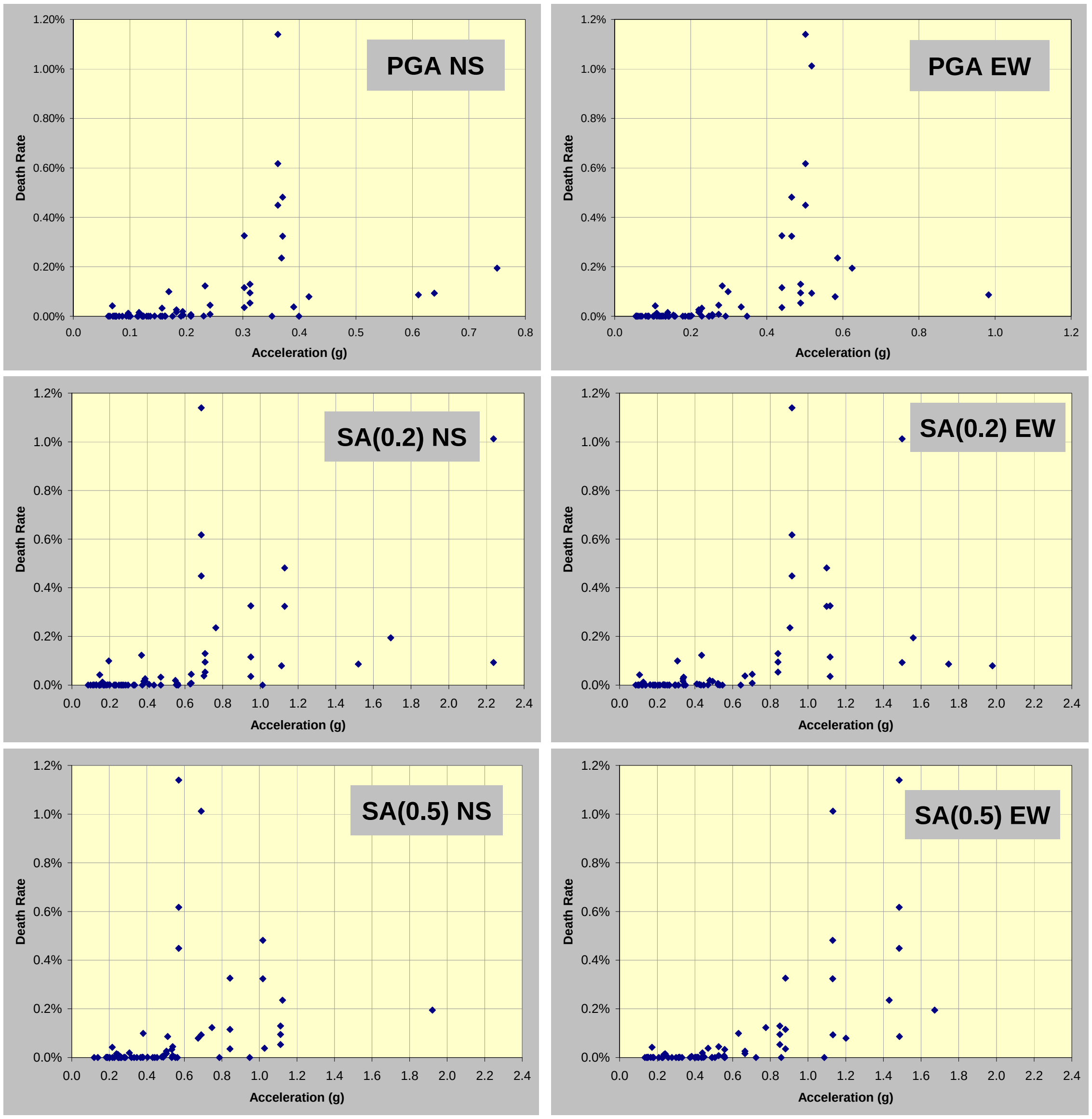
Table 5-2: Spearman Correlations and P-values Between Observed and Model-Predicted Deaths and Injuries for MMI and Epicentral Distance

Parameter	Death		Injury	
	Spearman ρ	P-value	Spearman ρ	P-value
Epicentral Distance	0.08	0.6984	0.36	0.4634
MMI	0.47	0.0133	0.62	0.0433

5.3.2 PGA and Spectral Acceleration

The association between casualties and engineering ground motion parameters such as PGA and spectral accelerations (SA) were also investigated. For this, ground motion records were processed and response spectra were calculated at several periods. The relationship between fatality rates with SA at periods of 0.2s, 0.5s, 1.0s, and 2.0s were examined in both north-south and east-west directions. Fatality rates were calculated on a township scale by dividing all-cause number of deaths in each township by the population of the township as recorded in the 2000 census. These relationships are presented as a series of plots in Figure 5-8.

North- South **East-West**



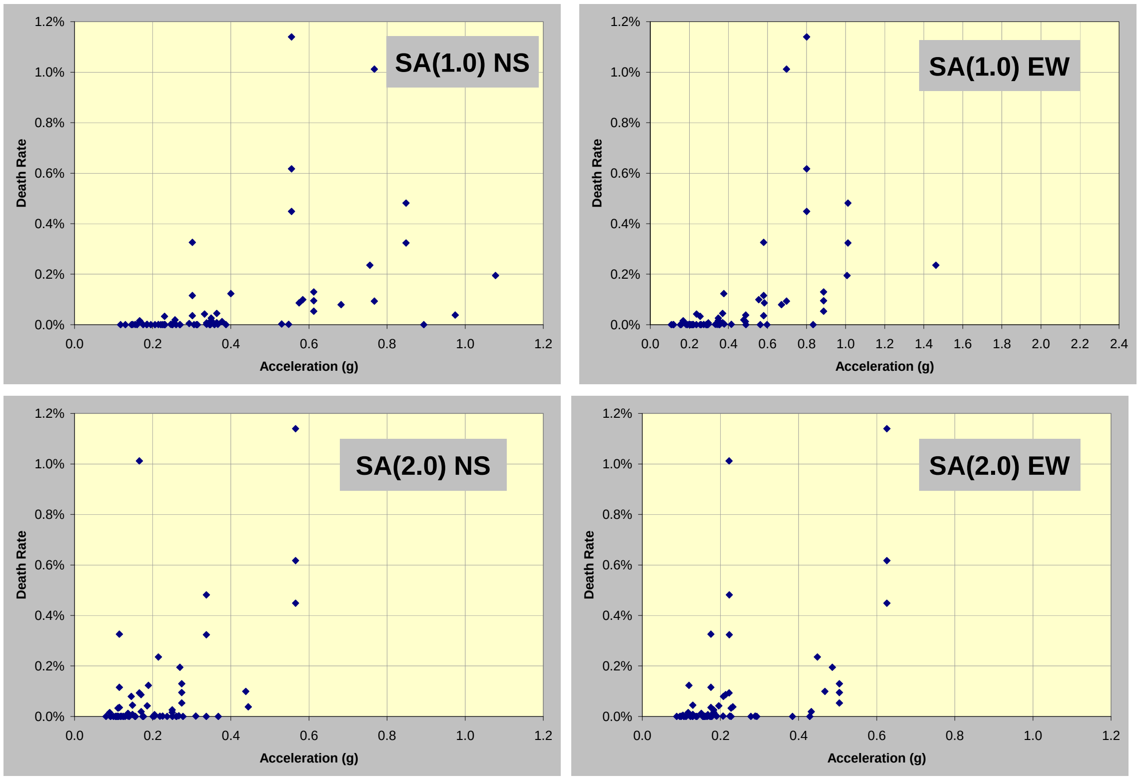


Figure 5-8: Death rates by North-South and East-West PGA and SA at periods of 0.2s, 0.5s, 1.0s, and 2.0s

In addition to observational methods a quantitative framework was used to examine the associations between fatalities and ground motion parameters. A regression analysis using a generalized estimating equation approach to account for clustering by township was performed and the goodness of fit evaluated by examining the Spearman correlations and p-values between the observed and predicted number of fatalities by each ground motion measure. The results of that analysis are shown in Table 5-3 below.

Table 5-3: Spearman Correlations and P-values Between Observed and Model-Predicted Deaths and Injuries for Ground Motion Measures

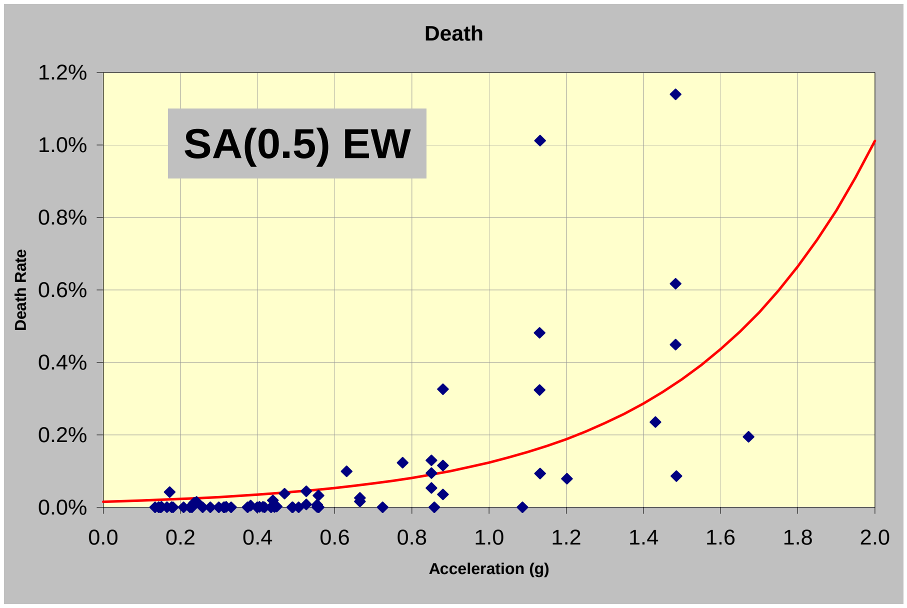
Parameter	Death		Injury	
	Spearman ρ	P-value	Spearman ρ	P-value
North-South PGA	0.30	0.0005	0.43	0.0017

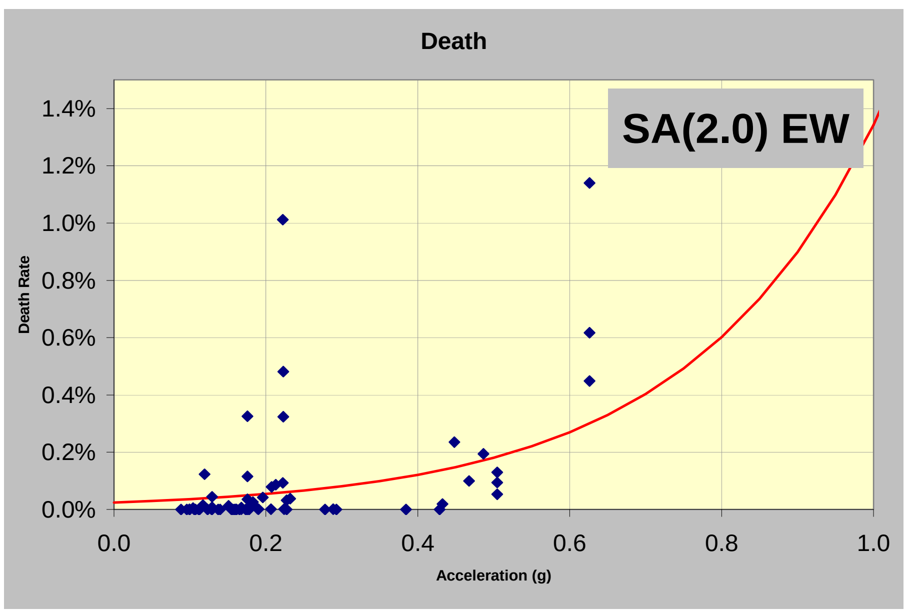
North-South SA 0.2	0.23	0.0398	0.40	0.0624
North-South SA 0.5	0.23	0.0199	0.48	0.2010
North-South SA 1.0	0.33	0.0022	0.51	0.0053
North-South SA 2.0	0.40	<.0001	0.65	0.0002
East-West PGA	0.35	0.0020	0.48	0.0140
East-West SA 0.2	0.26	0.0002	0.39	0.0012
East-West SA 0.5	0.58	<.0001	0.64	0.0009
East-West SA 1.0	0.42	<.0001	0.60	0.0045
East-West SA 2.0	0.48	0.0009	0.72	0.0097

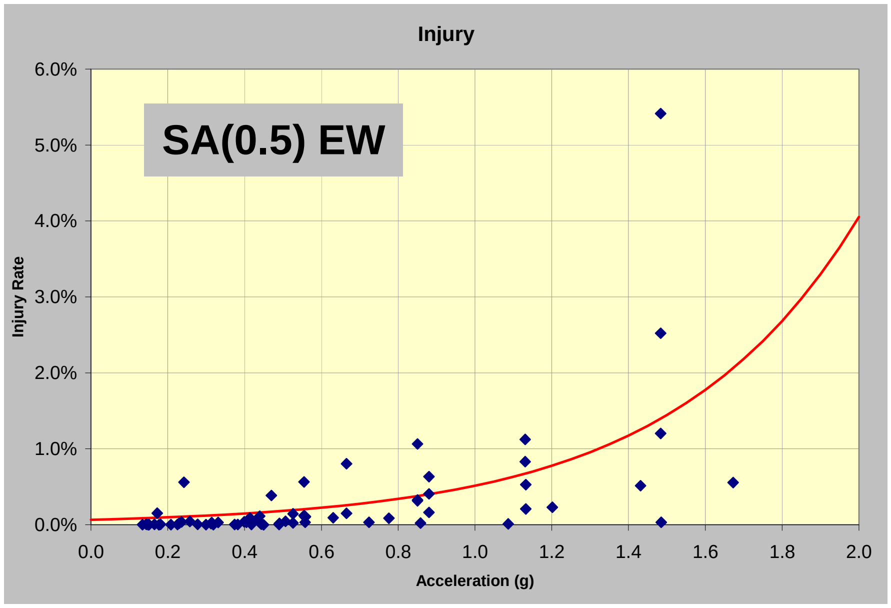
***Model: Logit ($P(Y_i=1| x_i)) = A_i + B_i*x_i$ where, Y_i is the number of deaths, x_i is measure of SA at a specific period, I, in g (9.8 m/s^2)

Ground motions in the E-W direction had higher correlations with death rates than those in the N-S direction. Noting that the fault orientation is almost perfectly N-S, casualties correlate better with fault-normal ground motions. In the North-South direction SA 2.0s corresponded best with both injuries and fatalities. This is likely because there were high-rise collapses in Taipei, which is 150 km north of the rupture. High-rise buildings respond to long period ground motion and so the association we see with SA 2.0 in the north-south direction is reasonable given the distribution of casualties. In general, the relationship between fatality rate and spectral response parameters is better characterized by longer period ground motions, 0.5s and above. This latter observation warranted a more detailed investigation of relationships with SA at various periods between 0.5s and 2.0s.

Among the SA at various periods between 0.5s and 2.0s, the 0.5s SA was most strongly associated with casualties. 2.0s SA also correlated comparatively well with both fatalities and injuries. Presented in Figure 5-9 are the plots of 0.5s SA and 2.0 SA against death rates and injury rates and the vulnerability corresponding casualty vulnerability function as determined by the regression analyses.







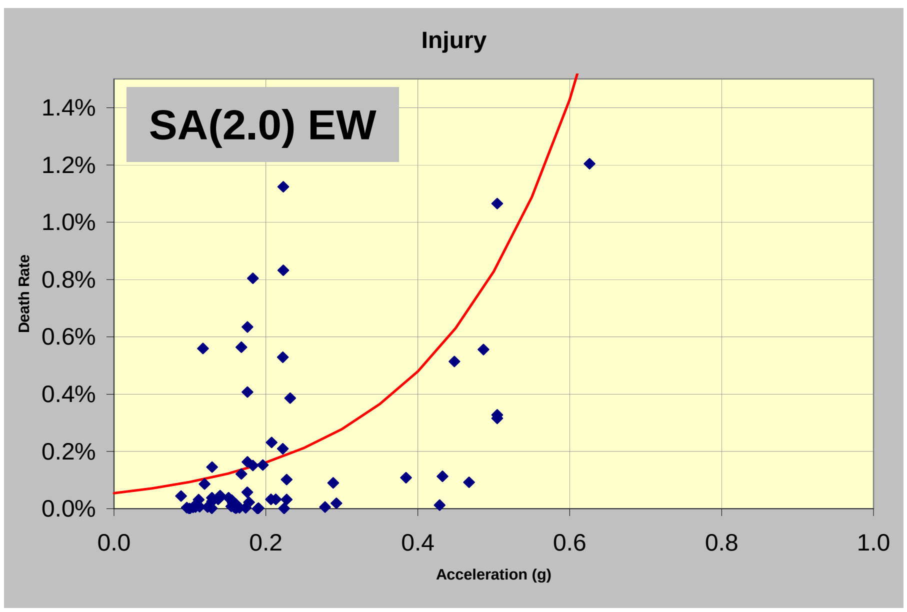


Figure 5-9: Death rate and Injury Rate by 0.5s and 2.0s SA

5.3.3 Building Class Specific Instrumental Ground Motion

The Spearman correlation coefficients and p-values between observed and predicted fatalities in each township, for each of the construction classes for each ground motion parameters are shown in Table 5-4. Only the East-West vulnerability relationships are shown, as E-W consistently performed better than N-S due to the orientation of the fault rupture. The vulnerability functions for the same construction differ substantially at different periods as illustrated in Figure 5-10.

Table 5-4: Spearman Correlations and P-values Between Observed and Model-Predicted Deaths and Injuries for Construction Class Specific Ground Motion Measures

Parameter		EW PGA	EW SA 0.2	EW SA 0.5	EW SA 1.0	EW SA1.2	EW SA 2.0
Mudbrick	Spearman ρ	0.49	0.51	0.56	0.53	0.64	0.67
	P-value	0.3788	0.2494	0.0694	0.2992	0.0418	0.0031
Masonry	Spearman ρ	0.54	0.53	0.71	0.54	0.47	0.53
	P-value	0.0970	0.0958	0.0034	0.0326	0.7669	0.3746
RC Low	Spearman ρ	0.33	0.20	0.51	0.29	0.52	0.35
	P-value	<.0001	<.0001	<.0001	<.0001	<.0001	0.0025
RC High	Spearman ρ	0.06	0.15	0.02	0.22	0.30	0.40
	P-value	0.1432	0.8182	0.1118	0.0044	0.0011	0.0030
Other	Spearman ρ	0.58	0.45	0.51	0.41	0.58	0.53
	P-value	<.0001	0.5043	0.3658	0.6445	0.0271	0.1420

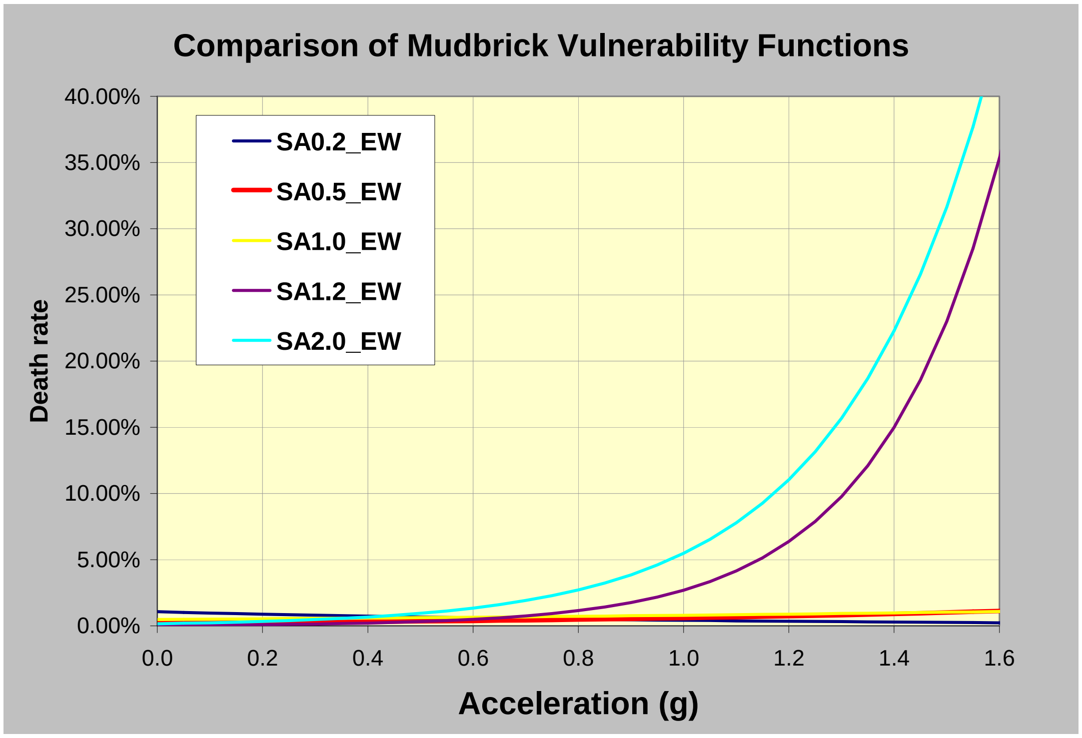
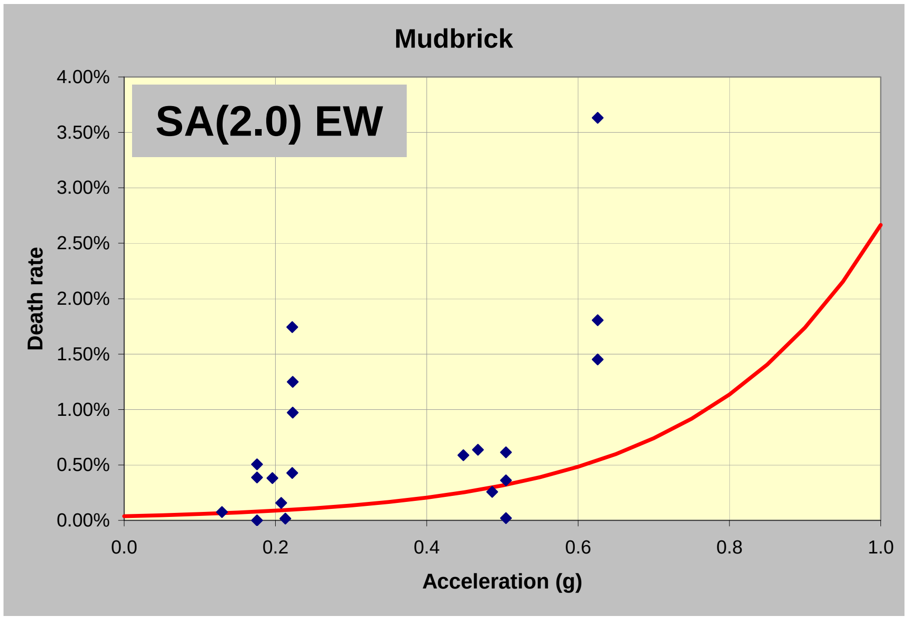
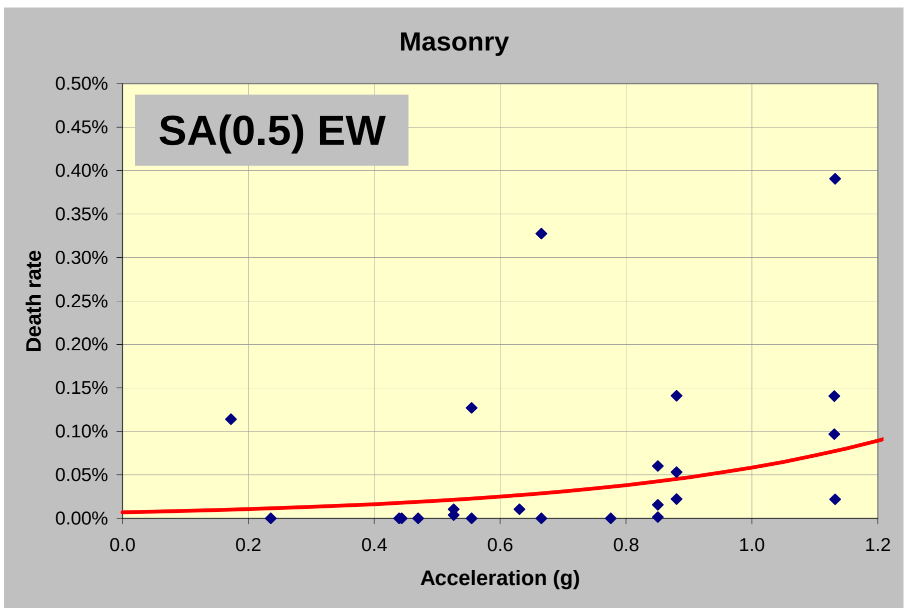
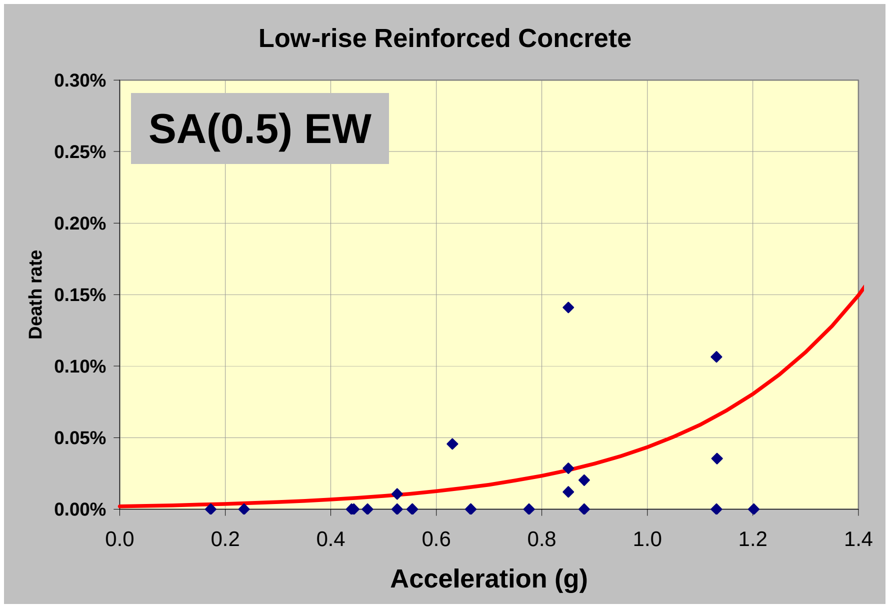


Figure 5-10: Comparison of Mudbrick Vulnerability Functions

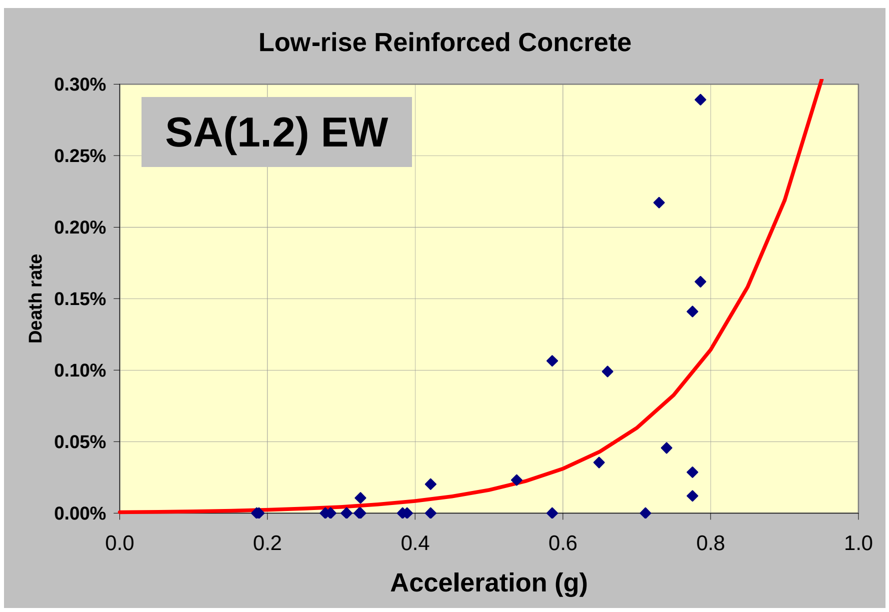
The model-predicted death rate and the resulting vulnerability functions for the building class specific analysis are shown in the Figure 5-11. The most strongly predictive period for each construction class is as follows: mudbrick-2.0s, masonry-0.5s, reinforced concrete low-rise-0.5s and 1.2s, reinforced concrete high-rise-2.0s, and other-1.2s.


Mudbrick
SA(2.0) EW
Death rate
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0.0
0.2
0.4
0.6
0.8
1.0
Acceleration (g)

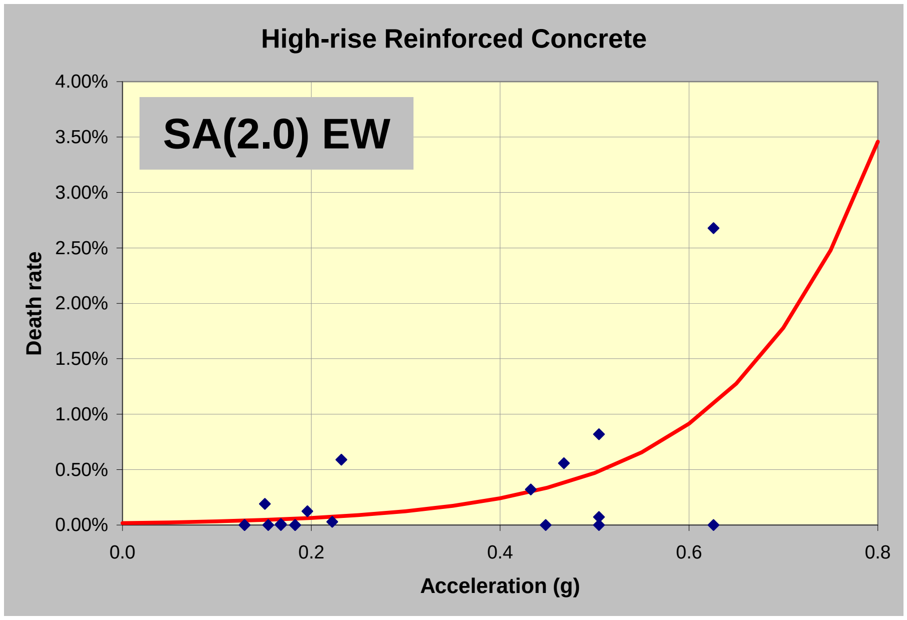

Masonry
SA(0.5) EW
Death rate
0.50%
0.45%
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Acceleration (g)



Low-rise Reinforced Concrete
SA(0.5) EW
Death rate
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Acceleration (g)



Low-rise Reinforced Concrete
SA(1.2) EW
Death rate
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0.0
0.2
0.4
0.6
0.8
1.0
Acceleration (g)



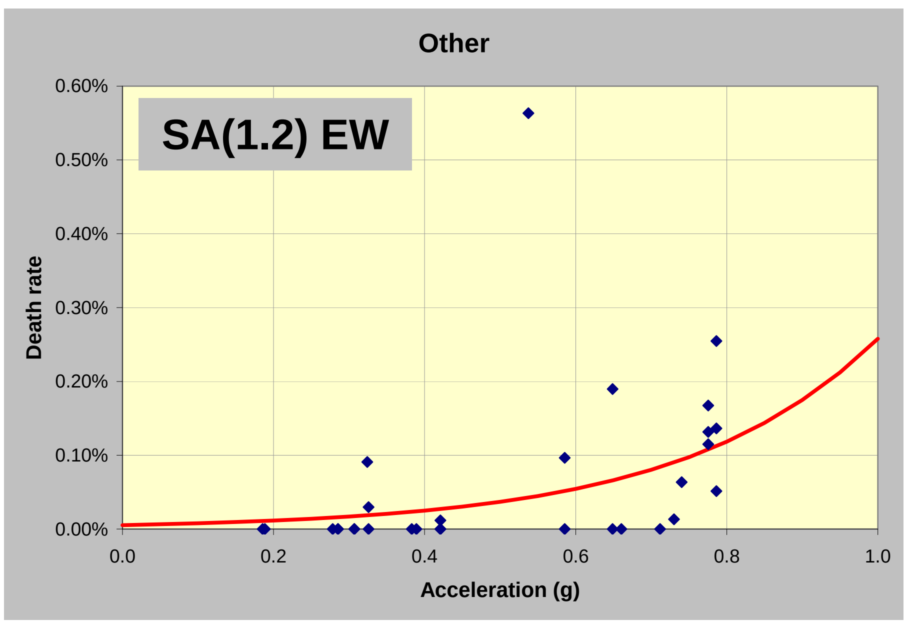


Figure 5-11: Death rates by SA at best fit periods for different building types

The attenuation function for each building class, shown in Figure 5-12, is consistent with previous studies of the impact of building class on casualties. Mudbrick has the highest casualty risk and reinforced masonry and reinforced concrete building perform well and similarly at moderate levels of ground shaking.

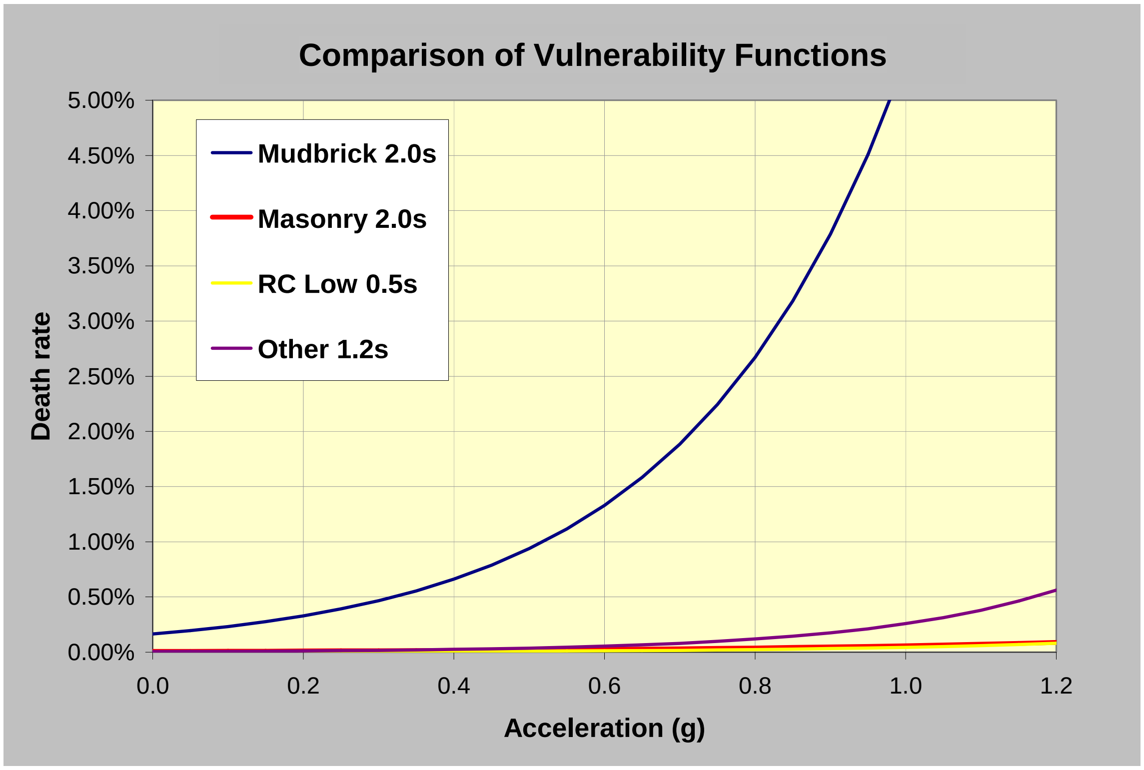


Figure 5-12: Comparison of Vulnerability Functions for all Construction Classes

5.4 Discussion

Summary of Key Results

This study aims to investigate the association between casualties and various ground motion parameters. Presented here are preliminary findings using data from only one event. The results of this study indicate that the association between ground motion and casualty data from a real event is consistent with structural engineering studies and laboratory tests of building response during earthquakes. This is one of the first attempts to derive casualty vulnerability functions from spectral response data and it was unknown as to whether the patterns seen in buildings would also be apparent in casualty data, which is sparse by comparison. The results also show that the association between spectral acceleration at the appropriate period and casualties is stronger that the association between MMI and casualties and epicentral distance and casualties. MMI and epicentral distance are commonly used in developing casualty estimates by emergency managers and by the public health community since they are simple to understand and produce (no knowledge of signal processing algorithms is required).

Strengths and Weaknesses

The limitations in the geographic resolution of the data require that the casualty data are aggregated to the township-level. The ground motion station used was the station closest to the centroid of the township, but depending on the size of the township and the location of the ground motions station the measurement of ground shaking likely differed from the actual ground shaking at the site of the casualties. In urban areas where there are more ground motion stations and the townships are small this difference is likely to be negligible. However, there were relatively few near fault strong-motion records are available from the hanging wall side of the fault. This made it necessary to use the same ground motion records for multiple locations with casualties and the difference in the measured ground motion and actual ground motion at the site of the casualty is likely to be more pronounced.

The relationship between casualties and ground motion is consistently better characterized by the longer-period (T > 0.5s) E-W components of the ground motions. The 0.2s SA did not correlate well with any of the casualty parameters. PGA was also investigated and E-W PGA was a slightly better predictor than 0.2s SA, but did not perform as well as the longer period ground motions. When instrumental ground motion measures are used in casualty studies it is most often PGA. The results of this study indicate that PGA does not correlate well and if a single instrumental ground motion metric is to be utilized PGV or a longer SA period would fit better.

The majority of the structures that caused casualties were low-rise mud-brick, masonry, and concrete structures apart from a few concrete high-rises that caused large number of deaths. Approximately 40 percent of the fatalities can be attributed to the collapse of mud-brick buildings. It appears that mud-brick exhibited a relatively long-period response to the earthquake ground motions since the fatalities corresponded best with 2.0s SA. This is consistent with the ductility of mud-brick buildings. Selection of the appropriate period is important as vulnerability functions can differ substantially by period. Some variation in the parameter is likely to not significantly impact results as long as the appropriate part of the response spectrum is being utilized for each building type.

Low-rise reinforced concrete buildings correlated best with 0.5s SA and1.2s SA. The majority of the low-rise concrete structures were 3 to 5 story buildings and it is expected that 0.5s SA would be the best predictor. The association with the longer 1.2s period was unexpected, but may be explained by soft-story construction. Low-rise concrete construction normally exhibits short period response, however soft story construction would cause the structure to respond the longer-period ground motion. There are no data to break the construction class analysis down further in terms of construction elements such as soft-story, but this relationship should be examined in more detail in the future. When examined in isolation, masonry structures were best associated with 0.5s SA, which is expected given the stiffness of masonry structures.

Although, long period SA is a better predictor of casualties in high-rise concrete buildings than short period SA, SA 1.0, SA 1.2, and SA 2.0 all performed similarly. One possible reason for this is that the structures varied in height from 6 to 16 stories and also in footprint size. Future research that further breaks the construction class down by building height and footprint size would help to refine these estimates. Additionally, several of the high-rise collapses with high death tolls occurred around 150 km from the epicentre in the areas with low ground motions. The collapse of several high-rise structures north of the rupture may help to explain why long-period N-S ground motions fit better than any of the short period N-S ground motions.

The failure mechanisms varied by high-rise building and included open space problems, failure of columns on the bottom story, poor construction quality, and irregular configuration (Tien, 2002). High-rise collapse can be a significant cause of casualties in earthquakes and the variation in mechanism of collapse and building characteristics makes it difficult to correlate high-rise collapse to a single ground motion parameter. Evaluation of collapse mechanisms on an individual building basis is important in improving seismic codes and preventing large numbers of high-rise collapse in urban areas.

Applicability and Importance of the Model and Future Research

Developing strong-motion relationships for casualty modeling is integral to increasing the utility of casualty models and more effectively incorporating engineering research. Despite its importance, casualty estimation is typically an afterthought in engineering studies or it is done by public health professionals with limited understanding of earthquake ground motion and structural dynamics. Hence, majority of post-event epidemiologic studies and earthquake casualty models still use MMI and do not explicitly account for construction type, despite the use of quantitative instrumental measures by the engineering community.

This study demonstrates that casualties at a regional scale do follow relationships that would be expected from individual building level response. More research is needed to further characterize these relationships and to develop universal vulnerability functions. Similar analyses should be done on future events in order to develop more robust and universally applicable functions that can be applied to areas with instrumental ground motion capabilities for a wider variety of building types. The eventual goal of the research would be to develop an automated system that could detect ground motion measures instantaneously post-earthquake and translate them into a map of the likely magnitude and distribution of casualties, which could be delivered to aid agencies immediately post-event.

CHAPTER 6 : APPLICATION OF SPATIAL MODELING TECHNIQUES TO CASUALTY ESTIMATION FOR THE 1976 TANGSHAN EARTHQUAKE

6.1 Introduction

Background

The 1976 Tangshan earthquake was the deadliest earthquake in recent memory. The death toll was comparable to the 2004 Indian Ocean Tsunami and official estimates are over 240,000 deaths and 165,000 severe injuries. The 7.8 magnitude earthquake struck on July 28th at 3:42am. The entire event lasted only 15 seconds and in that time the entire city and surrounding area were leveled.

The area was previously thought to have a low risk from high magnitude earthquakes, so consequently the majority of the residential construction was not seismically sound. In the area around the epicenter over 90 percent of residential buildings collapsed burying the inhabitants in rubble. Nearly all the lifelines and infrastructure were destroyed leaving the residents without assistance for an extended period of time.

Importance of the Problem

The experience of the Tangshan earthquake illustrates the devastating impact that a large magnitude earthquake can have on unprepared areas. Many areas of Asia and the world are at risk for sizeable seismic events and a critical first step in reducing earthquake morbidity and mortality is rapidly establishing the spatial extent and number of casualties. Needs assessment requires a set of tools that quickly allow for the prioritization of emergency services, search-and-rescue, and medical treatment that will minimize the loss of life. The development of casualty vulnerability functions is an important step in developing modeling techniques to understand and prepare for the impacts of earthquakes in order to minimize loss of life.

Goal of the Analysis

This analysis uses a logistic-based casualty vulnerability function developed from the 1999 Chi-Chi earthquake to predict the number and distribution of fatalities in the 1976 Tangshan earthquake (Sullivan, 2008b). Calibration by predicting historical event losses is an important component of the validation process for any predictive model. This paper will present a method for calibration of earthquake casualty vulnerability functions between earthquakes. It will assess the strengths, weaknesses and generalizabilty of a distance-based decay model centered on maximum coseismic slip to predict the spatial distribution of casualties in a historical earthquake, different from the earthquake used to develop the model initially.

6.2 Descriptive Background on the Tangshan Earthquake

6.2.1 Historical Seismicity

China is a country of active seismicity and has the longest historical earthquake record in the world. The stress accumulation and seismic release are non-uniform in time and space and the seismicity is characterized by having different active periods (Zhenliang, 1974). In the past century China has had 13 earthquakes resulting in 1000 or more deaths shown in Table 6-1 (USGS, 2006).

Table 6-1: Earthquakes in the Last Century Causing Greater than 1000 Deaths

Date	Magnitude	Location	Deaths

30 July 1917	6.5		1,800
13 Feb 1918	7.3	Guandong	10,000
16 Dec 1920	7.8	Gansu	200,000
24 Mar 1923	7.3		5,000
16 Mar 1925	7.1	Yunnan	5,000
22 May 1927	7.9	Tsinghai	200,000
25 Dec 1932	7.6	Gansu	70,000
18 Aug 1933	7.4		10,000
25 July 1969	5.9		3,000
4 Jan 1970	7.5	Tonghai,Yunnan	10,000
10 May 1974	6.8	Zhaotong,Yunnan	20,000
4 Feb 1975	7.0	Haicheng, Liaoning	10,000
27 July 1976	7.5	Tangshan, Hebei	250,000

The area affected by the Tangshan earthquake is in Northern China (Figure 6-1) and is part of the North China tectonic province. The North China tectonic province has the oldest continental crust in China, with geologic formations of the Precambrian age (Huixian, 2002). The province has two major tectonic systems consisting of an E-W tectonic belt and a NNE tectonic zone. These zones include the Tancheng-Luchiang fracture zone, the Hebei Plain fracture zone, the Taihang Piedmont fracture zone, and the Shansi Graben fracture zone (Huixian, 2002).

Prior to the 1976 Tangshan earthquake, the Tangshan region had been seismically active. In the 10 years preceding the earthquake there were 4 earthquakes greater than magnitude 7 in an area approximately the size of California. The seismic hazard was relatively high throughout the region though none of the 4 previous earthquakes had caused significant casualties.

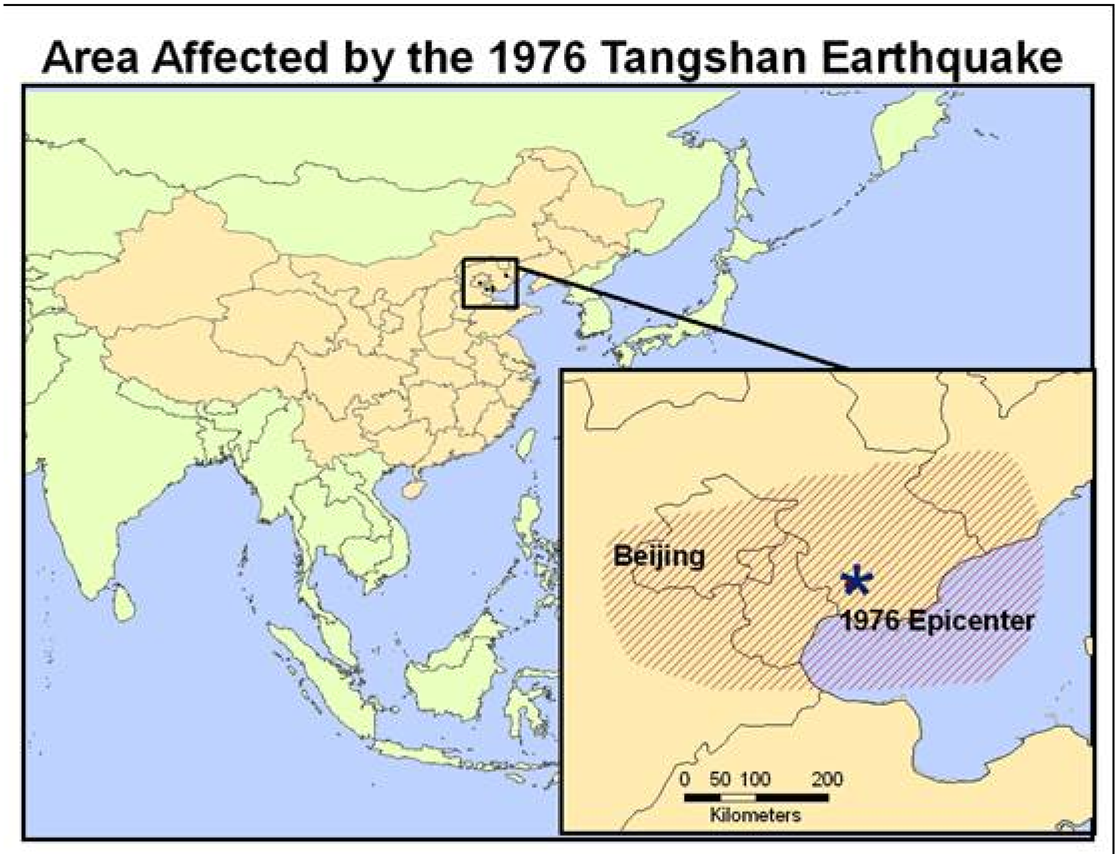


Figure 6-1: Area Affected by the Tangshan Earthquake

6.2.2 Seismological Aspects of the 1976 Tangshan Earthquake

The Tangshan earthquake had a magnitude of 7.8 and originated under the city of Tangshan, in the Hebei Province. The earthquake occurred at 3:43 am on July 28, 1976. The hypocenter was located under the southern part of Tangshan city at a shallow depth of 10km. The earthquake ruptured through the city in a northeasterly direction, and to a lesser extent in a southwesterly direction. The focal mechanism was strike-slip with evidence of surface faulting over a distance of approximately 10 km. The aftershock zone indicated; sub-surface faulting over a distance of approximately 140 km.

6.2.3 Construction Types and Techniques in Tangshan

The residential construction in and around Tangshan at the time of the earthquake consisted primarily of single story structures with stone or brick masonry walls and two or three story brick masonry buildings. There was a large inventory of building constructed before the middle of the 20th century and the building stock varied in terms of quality of construction. A portion of the commercial inventory was more recent.

In the 1960's there was a large-scale movement towards the construction of two and three-story brick-reinforced concrete buildings. These buildings constituted a significant portion of the commercial building inventory. There were also a small fraction of 5 to 8 story government buildings. Stores, hotels, restaurants and other commercial buildings were typically the only construction types that were internally framed.

In the Tangshan area the majority of the structures in rural areas were single-story houses with four beams and eight-columns. In the areas south of Tangshan most of the bearing walls were constructed of brick masonry or adobe. Many residences also had inner walls of brick and adobe. In the north and central part of the Tangshan area the residential construction was primarily constructed of rubble with a few structures utilizing brick, adobe, or cobblestone. Many of the residential structures had heavy roofs, which collapsed inward crushing residents.

Prior to the 1976 earthquake the city of Tangshan was thought to have only moderate seismic risk. The zoning laws at the time required that buildings in Tangshan be constructed for intensity VI and buildings in Beijing be constructed for intensity VII.

The intensities on the 1976 earthquake far exceeded the seismic capabilities of the building stock, especially the residential building stock.

In 1978, following the Tangshan earthquake, the State Seismological Bureau proposed new seismic map and remapped the intensity zones. The map gives the intensity to be expected during the next 100 years, but no probability is associated with the statement (Huixian, 2002). The new seismic building codes have resulted in the Tangshan area being rebuilt primarily out of reinforced concrete and reinforced masonry and the elimination of unreinforced masonry construction.

6.2.4 Casualties

The Tangshan earthquake was the most disastrous earthquake event in China in the 20^{th} century. Based on official government estimates the death toll is assumed to be in the range of 250,000. Some unofficial estimates claim many more than that. In addition to the deaths, 165,000 people were severely injured. Of those, close to 4,000 people lost limbs and 360,000 people suffered minor injuries requiring medical treatment.

Within the urban districts of Tangshan city an estimated 136,000 people were killed, 13 percent of the total population. Over 7,000 households, 4.5 percent of the total, in the urban district lost all family members. More than 80,000 people were severely wounded in the urban district, of which 1,700 people had injuries that left them permanently disabled.

There are several factors that contributed to the high number of casualties sustained during the Tangshan earthquake. The main reasons for the high death toll are unsafe construction practices, high population density, time of day, aftershocks, and poor response.

Construction Type Effects on Casualties

Most residential construction in the area was built without regard to seismic building codes. The predominant building material was unreinforced masonry with 4 beams and 8 columns. The beams and columns were the only components supporting the load and the heavy infill walls. The roof construction also contributed to casualties. The majority of the roofs were flat and heavy, with each square meter weighing as much as 400 kg. Brick and masonry walls were the primary load bearing structures and they do not perform well under seismic stress. When the walls failed the heavy roof fell inward crushing and trapping the occupants.

Population Effects on Casualties

The population density and construction density of the urban district were excessively high. In the epicentral area buildings occupied as much as 70 percent of the total surface area. The population density was 15,400 per square kilometer people. This is about 2/3 the population density of New York City, but Tangshan had very few high-rise buildings. The building density made it so no area was unaffected by earthquake debris, which made escape difficult and hindered the rescue effort.

Time of Day Effects on Casualties

The time of day the earthquake occurred contributed to high death toll. The earthquake occurred at 3:43 in the morning when the majority of inhabitants were asleep in their homes. The seismic quality of the residential construction was inferior to the commercial construction and the death toll may have been less if the earthquake occurred during working hours. In addition, those who were in a deep sleep were unable to respond and take precautions that may have prevented death or injury. It is estimated that in some areas 80 percent of people were buried under the rubble during the main shock of the earthquake.

The main shock of the Tangshan earthquake was followed by several significant aftershocks, which further damaged buildings and hindered rescue. A magnitude 6.5 aftershock occurred at 7:17 and another magnitude 7.1 aftershock occurred at 18:45 on the same day as the main shock. The large magnitude aftershocks further damaged structures, especially in the eastern part of the epicentral area.

Response Effects on Casualties

The city had no preparation in place for a large seismic event. The majority of the lifelines were fragile and disrupted by the earthquake. Over 500 km of railway lines and 225 km of highways suffered damage making access to the city extremely difficult. Public utilities were damaged including 70,000 water supply wells and the water mains and piping system. The water supply to Tangshan was completely cutoff and the supply was not restored until several months after the earthquake. Critical infrastructure such as hospitals, communication, and fire prevention were destroyed due to lack of seismic fortification. The critical infrastructure was completely disrupted leaving the area without power, water, communication, and medical supplies. Emergency operations were rendered almost useless for several days. People remained trapped in the rubble for long periods of time and without medical care those who had sustained injuries died. The lack of pre-event preparation and poor post-event response exacerbated the casualty impact of the earthquake.

6.3 Methodology

To apply the previously-developed distance based model centered on coseismic slip (Sullivan, 2008b) to the Tangshan earthquake, we acquired population estimates at the time of the event by 5km grid square and the construction class mix at the time of the earthquake. The distance from the centroid of each 5km grid square to the area of maximum coseismic slip was calculated using Arcview 9.1. The following sections describe the assumptions and approximations used to obtain this information from the sources available.

6.3.1 Population Data and Modeling Assumptions

In 1976 at the time of the earthquake, the city of Tangshan had about 1.2 million households. Approximately 270,000 households were located in the urban district. The total population of Tangshan was around 5.6 million people, 1.2 million of whom lived in the urban district. The total size of Tangshan city was around 50 square kilometers. The population density of the area around Tangshan is illustrated in Figure 6-2.

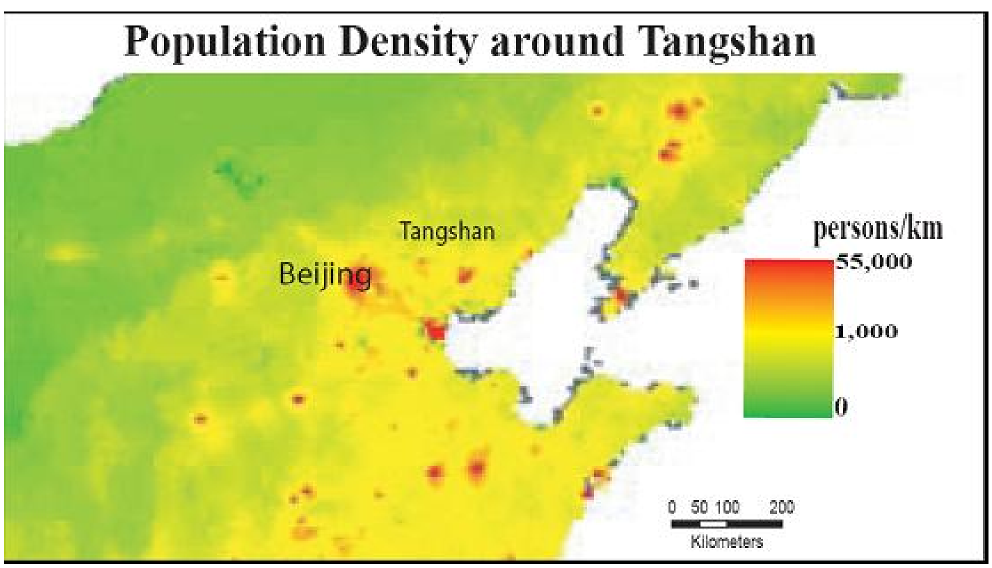


Figure 6-2: Population Density around Tangshan, Adapted from Yue, 2005

Nighttime residential population estimates were obtained by 5 km grid square at the time of the 1976 earthquake through personal correspondence with Institute of Engineering Mechanics, China Seismological Bureau. The grid squares covered all of Heibei province and Beijing city. This allowed for 5 km resolution of the resulting casualty model. Figure 6-3 illustrates the distribution of the 5km population grid in the Tangshan affected area. The 1976 population is approximately 75 percent of the current population in the region. Despite the large number of people killed by the earthquake the area has been rebuilt and due to population growth and immigration the current population has increased beyond that of the 1976 population.

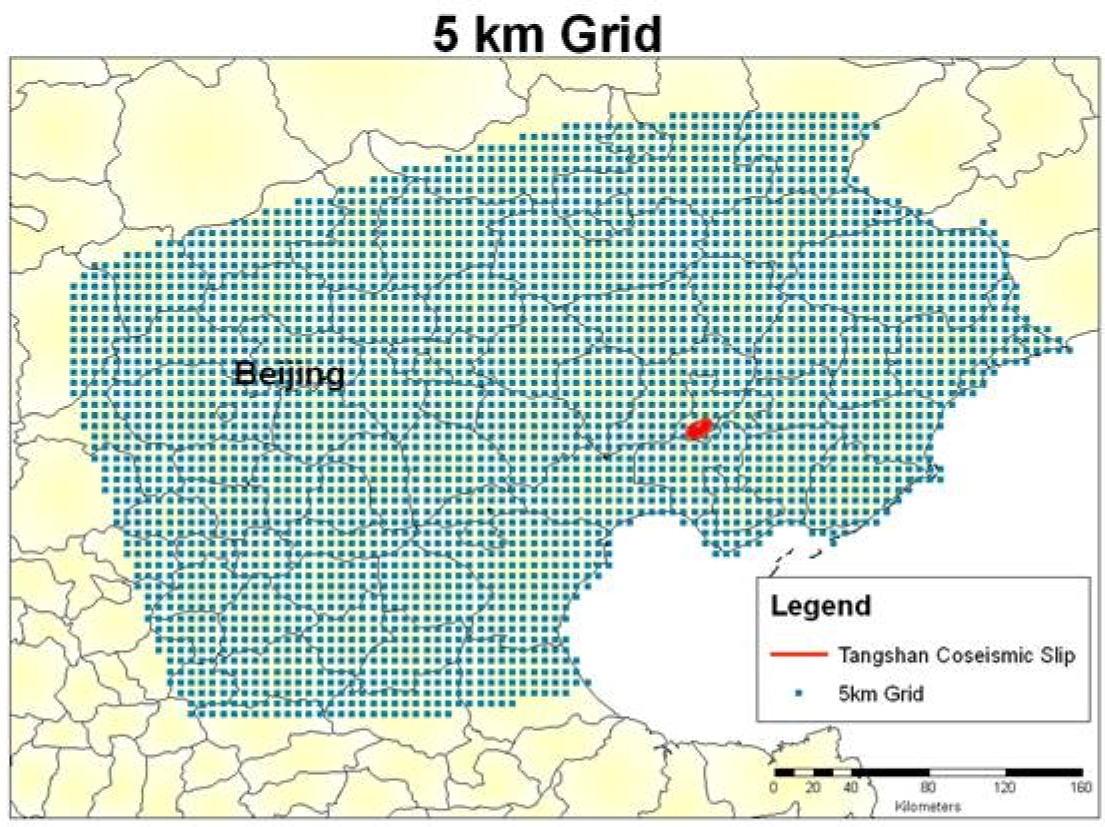


Figure 6-3: 5 km Grid in Tangshan Affected Area

6.3.2 Seismic Data and Modeling Assumptions

The coseismic slip distribution for the main shock of the 1976 Tangshan earthquake was taken from a 1997 paper by Huang and Yeong (Figure 6-4). The earthquake was a strike-slip rupture that caused 10 km surface rupture. The coseismic slip distribution was modeled as an approximately 10 km long and 5km wide region as shown by the red area in Figure 6-3. The distance based logistic decay model was centered on this region of maximum coseismic slip.

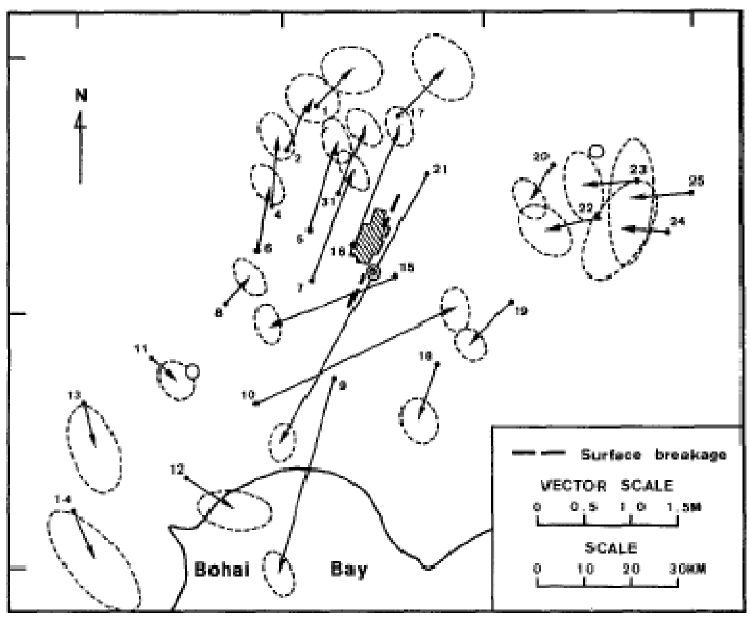


Figure 6-4: Coseismic Slip Distribution for the 1976 Tangshan Earthquake Taken from Huang, 1997

6.3.3 Building Inventory Data and Modeling Assumptions

At the time of the 1976 earthquake the residential building inventory was almost exclusively unreinforced masonry buildings. The event occurred at 3:43 am, so the great majority of the population is assumed to be in residential structures. In modeling the event the entire population was assumed to be in unreinforced masonry structures. The performance of unreinforced rubble stone, adobe, brick, and cobblestone has not been shown to be significantly different in seismic events. All building materials are considered to be extremely high risk construction types. One single casualty vulnerability function was utilized for the entire population.

6.3.4 Casualty Vulnerability Function Derived from Chi-Chi

The casualty rate vulnerability function was derived from the unreinforced masonry (mudbrick) curve developed based on the 1999 Chi-Chi earthquake in Taiwan. An extension of the curve was necessary as the 1976 Tangshan earthquake had a greater magnitude than the 1999 Chi-Chi earthquake. The intercept and rate of decay were adapted in order to account for the increased severity of the earthquake. The mudbrick casualty rate curve derived from township data has an intercept of 1.36% (0.67, 2.77%, 95% CI) and a decay rate of -0.134 (-0.22, -0.04, 95% CI). In order to create a curve appropriate for the Tangshan earthquake the complete building collapse rates were matched at two points, the region of maximum coseismic slip and where the building damage became negligible. In the villages closest to the region of maximum coseismic slip in the Chi-Chi earthquake the total collapse rate averaged 22.5%. The building collapse rate at the region of maximum coseismic slip in the Tangshan earthquake was 100% as shown in Table 6-2. The building collapse rate reached less than 1% at a distance of approximately 150km in the Tangshan earthquake and 50km in the Chi-Chi earthquake. The collapse percentages by distance for the Chi-Chi earthquake were interpolated from governmental damage surveys done immediately post event.

The building collapse methodology was selected because immediately post-event a micro-survey of building damage can be done within hours in order to calibrate the casualty function. A survey irrespective of building class can be quickly conducted to determine the damage at the area of maximum ground shaking and the extent of the earthquake damage. These estimates can be refined as better data become available, but a preliminary casualty estimate can be immediately ascertained for initial resource allocation.

Table 6-2: Building Collapse Rate by Distance for the Tangshan Earthquake

Seismic Intensity	Building Collapse Rate (%)	Area (km2)	Approximate Radius (km)
5	0	216,000	250
6	1	—	—
7	7	33,300	100
8	16	7,270	50
9	30	1,800	20
10	60	370	10
11	90	47	4
11+	100	—	0
Adapted from Nichols and Beavers 2003, originally from Shiono 1995			

Calibration of the Casualty Function Derived from Chi-Chi

The casualty vulnerability function derived previously for Chi-Chi was based on logistic model with decay in mortality with increasing distance from the maximum coseismic slip. We focus on the model for unreinforced masonry (mudbrick) buildings, as the residential building inventory in Tangshan in 1976 consisted primarily of unreinforced masonry structures. The casualty vulnerability function for mudbrick from Chi-Chi had the following form:

(1) $P_C(M|x) = 0.0136*\exp(-0.134 * x)$,

where the subscript C denotes that this function is for Chi-Chi and where x is the distance in kilometers from the area of maximum coseismic slip in the Chi-Chi earthquake, and M is mortality.

We assume that the casualty vulnerability function for Tangshan has the same form:

(2) $P_T(M|y) = c*\exp(d * y)$,

where the subscript T denotes that this function is for Tangshan, and y is the distance in kilometers from the area of maximum coseismic slip in the Tangshan earthquake. The mudbrick vulnerability function (Equation (1)) from Chi-Chi should not be directly applied to Tangshan, even if the building inventory is the same, because of differences in magnitude between the two earthquakes. First, the Chi-Chi casualty function must be modified to be relevant for Tangshan. A number of methods for calibration of logistic functions exist some of which are reviewed in Thoresen and Laake, 2000. We chose to calibrate the casualty vulnerability function using building collapse rate as a surrogate to calibrate both the intercept and the slope. The basic assumption for calibration is that by roughly matching the total building collapse percentages at two points the casualty vulnerability function can be quickly calibrated to be relevant for an earthquake of any magnitude. As discussed in the previous section this methodology was selected because the necessary building collapse data can be obtained immediately post-event and only rough estimates are necessary to calibrate the function.

Ninety percent of deaths in earthquake can be attributed to structural failure (Coburn, 1992). We assume that mortality in Chi-Chi (for a similar construction type) depends on the building collapse rate, and that the dependency on building collapse rate (for a similar construction type) is the similar in Tangshan. In symbols:

(3) $P_C(M|x) = g(B_{C,C}(x))$ and $P_T(M|y) = g(B_{C,T}(y))$

where $B_{C,C}(x)$ and $B_{C,T}(y)$ are the building collapse rates at distance x in Chi-Chi and distance y in Tangshan, respectively, and g( ) is the function relating mortality to collapse – *assumed* to be the same in the two earthquakes, after accounting for construction type.

With these assumption (Equations (2 and 3)), we can equate the model-predicted mortality in Chi-Chi (Equation 1) at a distance x, to the model-predicted mortality in Tangshan at a distance y, provided $B_{C,C}(x) = B_{C,T}(y)$. If we do this for two such points, we obtain 2 Equations in 2 unknowns (c, and d in Equation 1), which can be solved for c and d – yielding the calibrated Equation (2), now with the calibrated coefficients.

The building collapse rate was 22.5% at 0 km in Chi-Chi ($B_{C,C}(0) = .225$) and was also 22.5% at 40km in Tangshan (($B_{C,T}(40) = .225$)). Similarly, the building collapse rate first dropped to <1% at 50 km in Chi-Chi ($B_{C,C}(50) = .01$), and dropped to <1% at 150km in Tangshan (($B_{C,T}(150) = .01$). Equating the casualty vulnerability functions at these 2 points yields:

$$0.0136*\exp(-0.134 * 0) = c*\exp(d * 40)\ P_T(M|40),$$

$$0.0136*\exp(-0.134 * 50) = c*\exp(d * 150\ P_T(M|150),$$

Solving these 2 Equations, yield c = 0.155, d = 0.0609, or

$$P_T(M|y) = 0.155\exp(-0.0609*y).$$

The resulting Tangshan vulnerability function and the Chi-Chi mudbrick vulnerability function used to derive the relationship are shown in Table 6-3 and Figure 6-5. The resulting slope for the Tangshan casualty function is within the 95% confidence interval for the Chi-Chi function. The calibrated model was used to predict the rate and number of fatalities for the population in each 5km grid square. Sensitivity analyses were performed by changing the calibration points.

Table 6-3: Mudbrick Casualty Vulnerability Functions for Chi-Chi and Tangshan

	Intercept (95% CI)	Coefficient (95% CI)
Chi-Chi	1.36% (0.67%, 2.77%)	-0.134 (-0.22, -0.04)
Tangshan	15.5%	-0.061

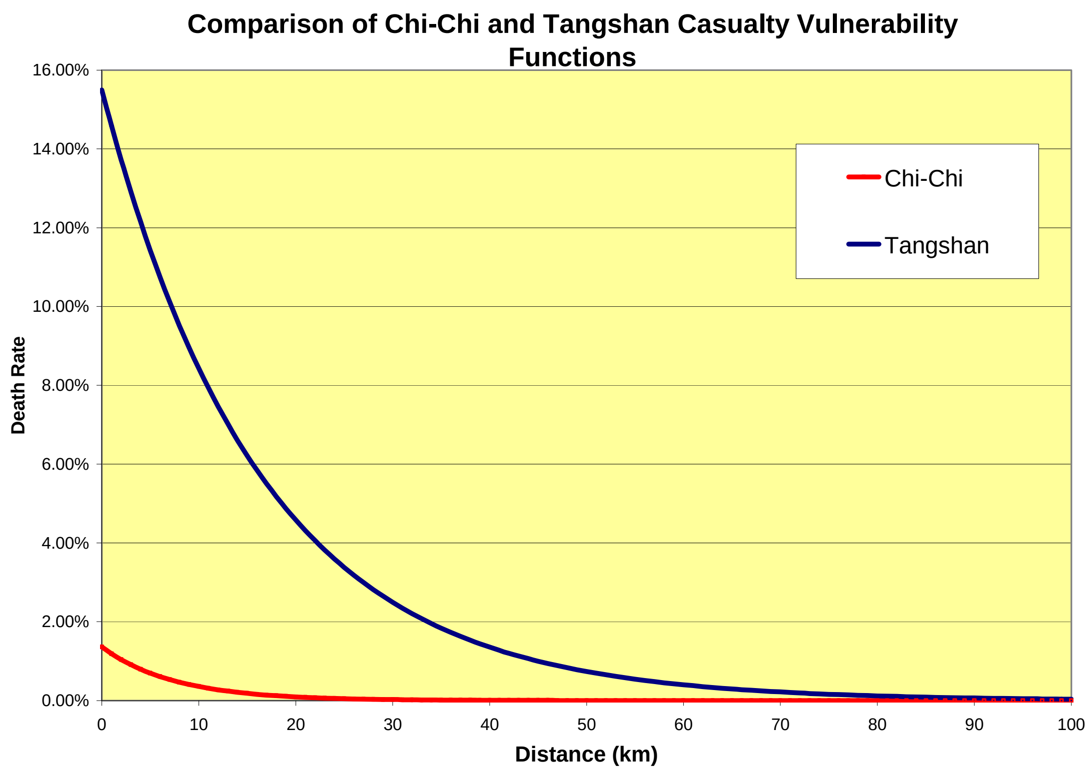


Figure 6-5: Casualty Vulnerability Functions for the Chi-Chi and Tangshan Earthquakes

The goal is to translate a known curve based on easily obtainable information in the hours following an earthquake. The method presented above is one way to calibrate the function from one event to another using an approach that is easily replicable in order to quickly estimate the magnitude and distribution of casualties. Prior to applying either of these curves to another event a calibration must be performed. As more data become available the curves will continue to become more universal, but at the time of this research a calibration of the casualty vulnerability curves using building collapse rates or another methodology is necessary in order to accurately estimate the magnitude and distribution of casualties for events of different magnitudes.

6.3.5 Statistical Criteria Comparing Modeled to "Observed" Results

A Spearman rank correlation test was used to compare the categorization of the modeled results to the categorization of the only historical record of the spatial distribution of casualties, the map shown in Figure 6-6. The "observed" data were a painting of casualty rankings based upon an (Modified Mercalli Intensity) MMI scale composed after the 1976 Tangshan earthquake. The casualty categories displayed were not attached to any numerical values and the map lacked a coordinate system, so the image had to be heavily processed before it could be compared to the modeled output.

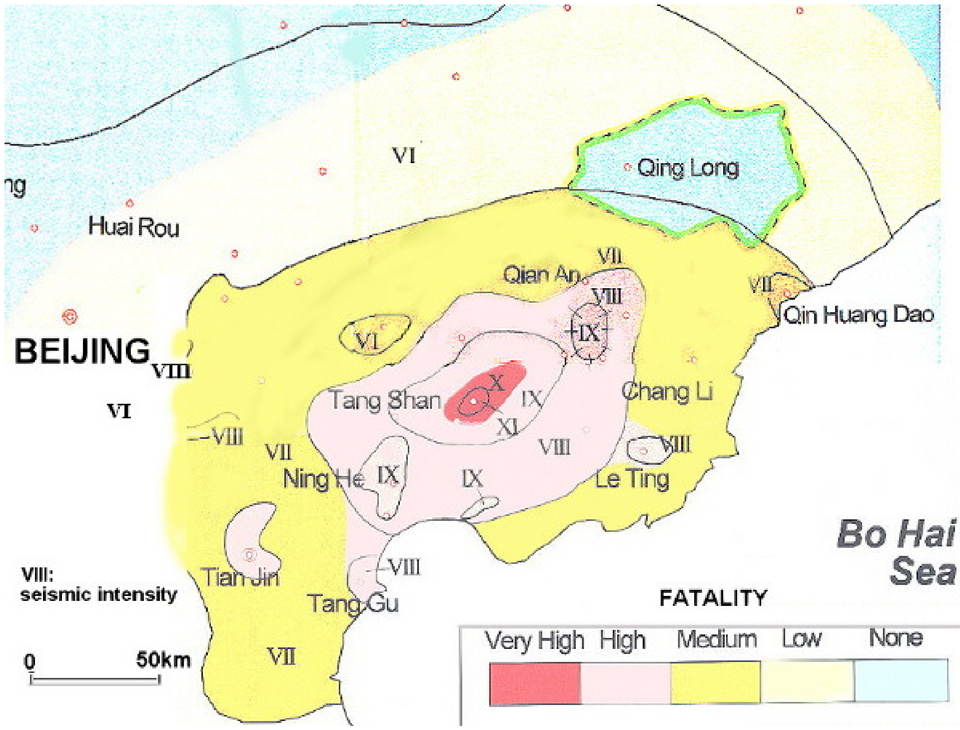


Figure 6-6: Map of Actual Fatalities from the 1976 Tangshan Earthquake (Xiaohan, 1996)

6.3.6 Spatial Mapping of Modeled and "Observed" Results

The painting was assigned a coordinate grid using the georeferencing capabilities in ArcMap 9.1 (ESRI, 2005). This was accomplished by doing a spatial join of the painting and a 5 km square grid of the Tangshan region shown in Figure 6-3. Eighteen control points were chosen from cities and distinct bends in the coastline. The join was completed using ArcMap's auto adjust option with a first order polynomial. By making the grid partially transparent and displaying it on top of the painting, all of the grid squares could be selected for one color swath of the painting. The entries in the attribute table of these selected squares were exported. This same process was repeated for each of the different color categories in the painting. The combined data were added into ArcMap, joining it to the 5 km grid, and choosing death rank as the variable by which to color code the map resulted in a display similar to the underlying painting. The resulting map of observed data shown in Figure 6-7 was used for comparison with the modeled data.

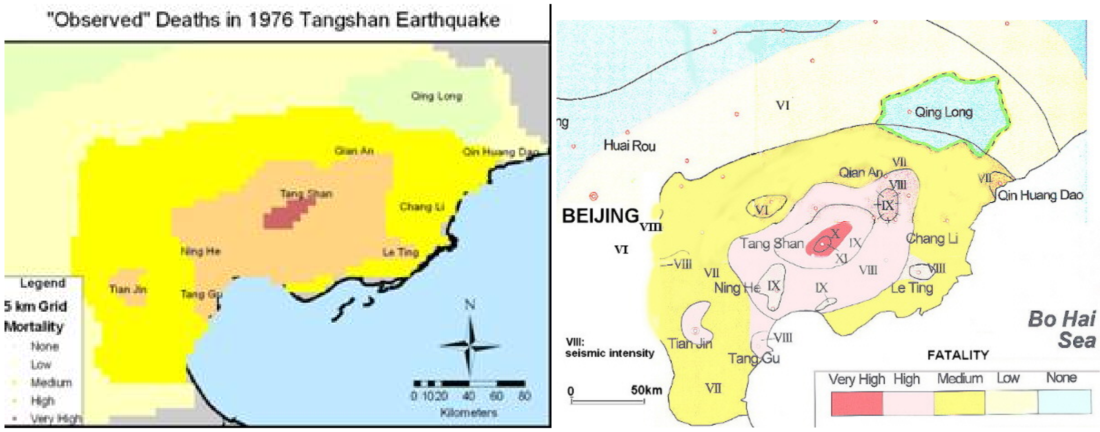


Figure 6-7: Comparison of Tangshan Casualty Drawing with Map used for Comparison

The modeled data were initially numerical by grid square as shown in Figure 6-8. In order to make comparisons with the categorized casualty rankings in the observed map, 5 casualty categories were created out of intervals from the modeled death count. Using manual breaks, the intervals were adjusted with more attention was paid to the highest casualty categories than the lowest, as this has the most significance for future models. The ranges of each chosen interval were then recorded, and used to convert the actual death count into a 5 category rank with the same 0 to 4 scale as that of death rank in the observed data. The classification was performed blind based on natural breaks in the data by an analyst unaware of the observed map based on orders of magnitude of numbers of casualties. Over 1,000 fatalities in a 5km grid square is classified as a 4, 100-1,000 as 3, 10-100 as 2, 1-10 as 1 and 0 as 0. The resulting categorical map is shown in Figure 6-9.

The statistical correlation coefficient was determined using a Spearman rank correlation test.

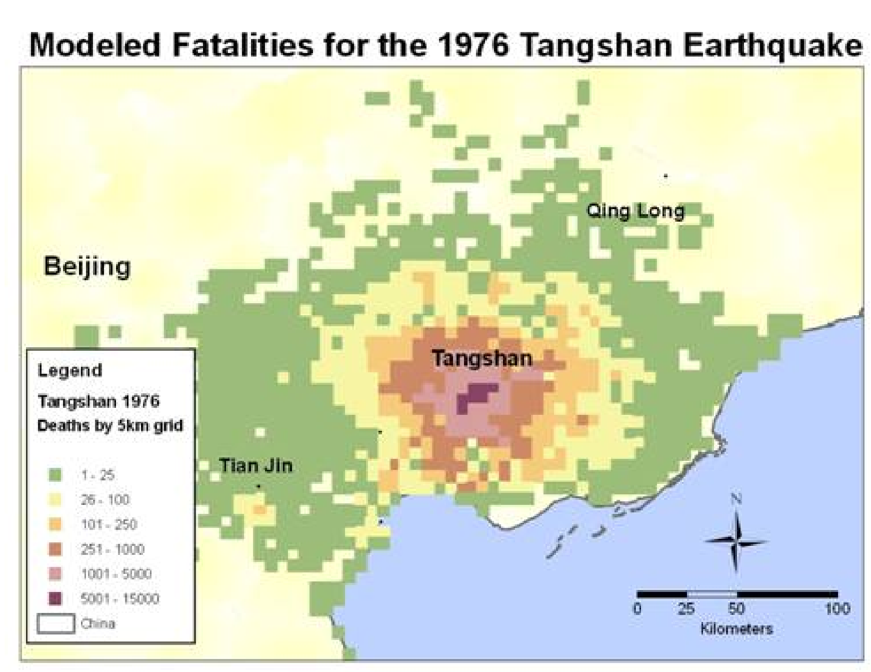


Figure 6-8: Map of Model Fatalities for the 1976 Tangshan Earthquake

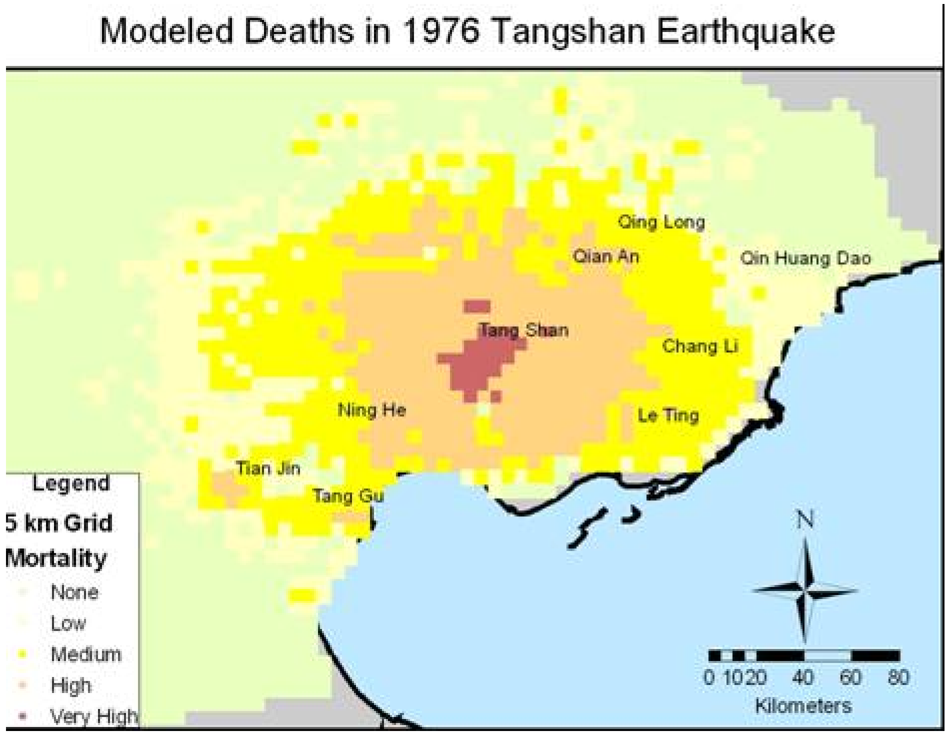


Figure 6-9: Categorized Modeled Deaths for the Tangshan Earthquake

6.4 Results

The total number of modeled fatalities was 234,951. This can be compared to the 242,000 fatalities officially reported by the Chinese government. The modeled spatial distribution of the fatalities is shown Figure 6-8 and the distribution of fatalities as drawn post event is shown in Figure 6-8 above. An overlay of the observed and modeled distribution of fatalities is shown for comparison in Figure 6-10. The high fatality areas of the modeled and observed distribution are similar, but the fatalities taper more quickly in the modeled than observed. Selection of alternate calibration points changes the slope of the decay and the intercept, but the general shape and magnitude of the casualty distribution stays similar. The Spearman correlation coefficient between the categorization of the observed and modeled deaths was 0.732, which increased to 0.809

when the large number of zeros in the outlying areas away from the epicentral area were removed from the dataset. Changing the cutoff points for the classification of the modeled results has relatively little impact on the Spearman correlation coefficient. In a sensitivity analysis the lower cutoff was changed from 1000 to 2000 for category 4, 100 to 250 for category 3, 10 to 50 for category 2, category 1 remained at any casualties and category 0 remained at 0 casualties, the Spearman correlation coefficient changed from 0.723 to 0.729.

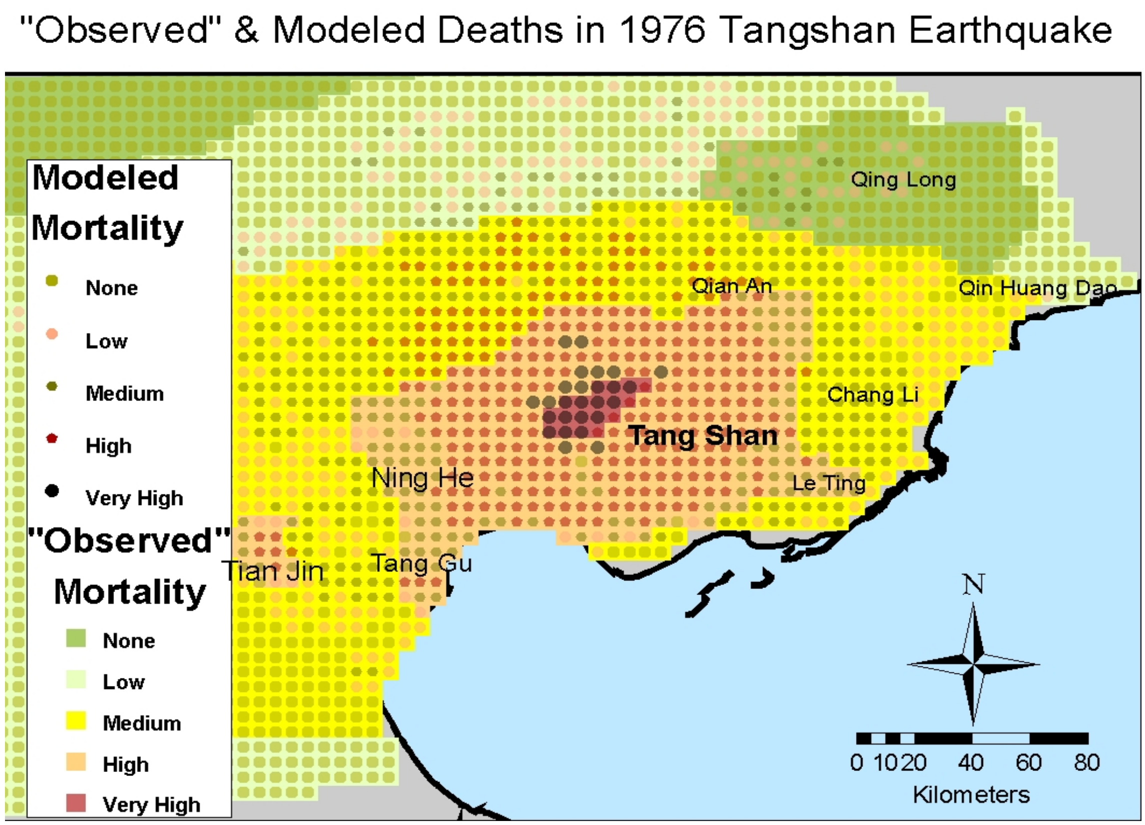


Figure 6-10: Overlay of "Observed" and Modeled Maps

6.5 Discussion

Summary of Results

The distance-based casualty model does a reasonably accurate job of predicting both the magnitude and spatial distribution of fatalities sustained during the Tangshan earthquake. The analysis is limited by the lack of quality post-earthquake casualty data for the Tangshan earthquake, but despite these limitations there is relatively good agreement between modeled and observed results. The model underestimates the total extent of casualties, but there is good agreement between the modeled and observed map in the high casualty areas. Initial estimates of total fatalities are often orders of magnitude different from actual event losses. In this case the total number of modeled fatalities differs by 3.3 percent from the actual recorded number. The modeled results presented above are accurate enough to have utility in post-event response and resource allocation.

Strengths and Limitations

The approach presented here describes a method for calibration of the casualty function derived from Chi-Chi that can be applied elsewhere. While the procedures used for evaluation did yield a mechanism for assessing the newly calibrated model, the comparison of the observed data from the painting with the modeled output was highly subjective at many steps. The painting is not an ideal source of observed data. The categorizations are based on MMI levels, which are themselves based upon the ability of a chosen sample of people in the earthquake to assign a numerical value to the intensity of shaking they felt. The map uses a non-specific 5 interval scale of casualty rates. Additionally, it is unlikely that the actual MMI levels in the Tangshan earthquake varied spatially with the exact clean boundaries drawn on the map.

There is no coordinate system assigned to this map, although a linear distance scale is supplied. The spatial join used to attach the map to a known 5km grid was necessary to create a discretization of the data, but skewed the map in the process, thereby distorting the color codings. The spatial join itself was based on the best abilities to match equivalent features, but was by no means an objective process, as cities were not marked clearly on the painting and the coastlines on each map were not the same shape. Additionally, assigning squares in the grid to their corresponding categorizations also involved personal judgment calls at the boundaries in which grid squares overlapped with multiple color swaths. Creating the historical map in a GIS format was subjective at points, but it did provide a method for comparison of the modeled results to non-digitized data, which is an important component in validating the models against historical events.

The actual comparison to the modeled data was also subjective. The ranges of the painting categories are unknown, so the modeled data had to be broken into intervals based on judgment. Furthermore, the modeled map was categorized by casualty counts whereas the painting was categorized by perceived intensities of ground shaking. As a result of these inconsistencies, comparing the artificial death rank scales between the modeled and observed maps likely increases the similarity between the two data sets.

Applicability of the Model

Despite these shortcomings the model appeared to be accurate enough to have utility in post-event response and did a relatively accurate job of predicting the overall magnitude and distribution of casualties. The model was unable to capture the human behavioral elements. The county of Qinglong undertook extensive preparation measures before the earthquake and as a result sustained no casualties. The model was aided by the relative simplicity of fault rupture and by the uniformity of the building inventory distribution throughout the region. This example demonstrates that distance based vulnerability functions can be translated between events and can give relatively accurate estimations of the number and distribution of fatalities.

Further Research

Further research needs to be done to refine and develop vulnerability functions for other building classes. The method is universally applicable regardless of the complexity of the fault rupture, but a more scientific criteria needs to be developed to translate between events. With more refinement and research this method can be used to quickly develop a spatial map of casualties for anywhere in the world where the population, inventory, and seismic characteristics are known.

CHAPTER 7 : CONCLUSIONS

The Chi-Chi earthquake provides a unique opportunity to begin to develop spatial casualty models. This is the first mass-casualty earthquake with both comprehensive strong-motion data and morbidity and mortality data with geographic identifiers. The availability of high-quality ground-motion and mortality data allows for the development and testing of casualty modeling frameworks that can be applied to future events.

Mitigating morbidity and mortality in seismic events is dependent on the ability to understand the magnitude and geographical extent of an earthquake's impact. Earthquakes give no warning; consequently, pre-event hazard mitigation and rapid response and recovery are the only mechanisms with which to reduce impacts. Casualty models can be used during response and recovery in order to inform decisions about search and rescue, the location of critical communications, food, medical, and water needs. This will help to optimize resource allocation and lead to more people receiving aid in the critical first 24 hours following the earthquake. Spatial models of casualties are also vital in understanding the magnitude and distribution of casualties in a potential earthquake in order to inform mitigation decisions made pre-event. These models can improve mitigation measures for critical infrastructure, such as hospitals and supply caches, assist with properly targeting the location of education programs and retrofitting, and aid in adjusting growth patterns to minimize vulnerability.

This dissertation develops earthquake casualty models centered on three different parameters and evaluates the predictive ability of these models. The maximum coseismic slip provides a better framework than either of the two commonly used spatial centering parameters: epicenter and surface rupture. The strengths and weaknesses of the coseismic slip methodology are further evaluated and additional predictive variables are incorporated into the model, including construction class and additional geologic data. This results in the development of construction class specific casualty vulnerability functions. The relationship between specific ground motion parameters and earthquake casualties is quantified and found to be in accordance with what would be expected from structural engineering research. Finally, the vulnerability functions are used to develop a spatial model of a historical event, the 1976 Tangshan earthquake.

The study of spatial and ground motion relationships and casualties is in its infancy. This dissertation provides a simple model applicable to complex faulting systems that is a key element in improving how essential decisions are made. Using coseismic slip as a framework for casualty modeling allows for more accurate modeling of complex fault ruptures. The predictive ability of the model could be improved by accounting for complexities of the fault rupture such as directionality of the rupture and anisotropy in the propagation of seismic waves and by having a more detailed building inventory. More specific construction class information including ATC class, seismic retrofits, information about soft stories, and building age would greatly improve casualty estimates. Limitations in the geographic resolution of the data required that the both the casualty and inventory data be aggregated geographically. Better geographic resolution of the construction class, geologic, and casualty data would improve the model. The most important limitation is that the casualty functions are derived here are from only one earthquake. This research is ongoing and should be viewed as preliminary until data from additional events is incorporated to refine the casualty vulnerability functions and ensure applicability to areas that have building inventories different that those in Taiwan. Another major limitation is the ability to model high-rise collapse, which has the ability to cause a large number of casualties and is inadequately captured by a distance-based model.

The calibration against the 1976 Tangshan earthquake using the vulnerability functions derived from Chi-Chi introduces a method for translating existing curves from past events to future earthquakes. The resulting model of the overall magnitude and distribution of casualties was accurate enough to have utility in post-event response. The distance-based method presented here reasonably represents near fault mortality, but may not adequately capture mortality away from the fault, which is most likely to be in high-rise structures. Due to the low probability and high consequences of the collapse of engineered structures there is no easy method for developing spatial models or vulnerability functions for high-rise collapse.

Incorporating instrumental ground motion into casualty models will help with better prediction of casualties in high-rise structures and allow for quantitative, independent, and generalizable vulnerability functions applicable to areas with different building inventories and geologic substrates. In areas with strong-motion networks ground motion data is available instantaneously after an earthquake and it can be used to inform response and recovery decisions and to appropriately deploy scarce resources to minimize loss of life. In addition, updating the casualty modeling framework to incorporate current engineering and seismic principles allows for more effective multi-disciplinary cooperation and the ability to apply cutting-edge research in other fields to casualty modeling. Critical choices will be better informed by building seismologic principles into a base modeling framework and changing the way emergency managers and public health practitioners conceptualize earthquakes.

Further research is needed to refine the casualty vulnerability functions for universal applicability. In order to improve casualty modeling, there must be a shift in the way post-earthquake morbidity and mortality data is collected. Epidemiologic studies have historically identified individual-level risk factors such as age and gender, but have failed to capture critical information like location relative to the origin of the shaking or construction characteristics of the building. Structural engineers typically do comprehensive post-event surveys in order to understand the failure mechanisms of buildings in earthquakes. Similar rigorous data collection has not been extended to casualties. In addition, there is a lack of multidisciplinary cooperation in data collection. Post-event reconnaissance missions should be conducted by seismologists, engineers, and epidemiologists together. Epidemiologic research has not incorporated relevant research from other disciplines. This has resulted in casualty model development being an afterthought of the engineering community and of limited utility to emergency managers and the public health community.

Risk assessment models, which can incorporate seismic, engineering and population data, are essential tools for understanding and preventing earthquake morbidity and mortality. With the advent of tools such as GIS and advances in modeling seismic hazards and structural performance the tools exist for the development of relevant casualty models. Multi-disciplinary cooperation and more sophisticated and informed data collection will allow for the refinement of casualty relationships. These models can then be applied globally to supply critical knowledge in order to reduce the lives lost in future earthquakes.

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